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AN AEROELASTICIAN'S PERSPECTIVE OF WIND TUNNEL AND FLIGHT EXPERIENCES WITH ACTIVE CONTROL OF STRUCTURAL RESPONSE AND STABILITY

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SUMMARY

The paper gives an aeroelastician's perspective of the active controls technology area based on a review of most of the wind-tunnel and flight tests and actual applications of certain active control concepts since the late sixties. The distinction is made between so-called "rigid-body" active control functions and those that involve significant modification of structural elastic response or stability. Both areas are reviewed in detail although the focus is on the latter area. The basic goals and major results of the various studies or applications are summarized, and the anticipated use of active controls on current and near-future research and demonstration aircraft is discussed. Some of the "holes" remaining in the feasibility/benefits demonstration of active controls technology are discussed.

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INTRODUCTION

Since the early seventies there has been a growing recognition of the potential gains in aerodynamic efficiency and structural weight savings that can be realized through the use of active controls to alleviate gust loads, improve ride quality, and reduce fatigue; reduce maneuvering loads; and suppress airframe instabilities such as flutter and divergence. As a result, there have been significant advances on both the analytical and experimental fronts of this relatively new technology area. Basically, experiments (wind tunnel and flight) have been used to validate theory or analysis, to evaluate feasibility, and to demonstrate predicted benefits. Each experiment usually focused on a particular application of the broad spectrum of active controls technology but over the years the distinctions between control functions have become diffuse so that for the relatively casual observer it may not be clear just what applications or benefits have been demonstrated and where there are still deficiencies. This paper attempts to put into perspective the results of the various wind-tunnel and flight experiments performed under the banner of "active controls."

Perhaps first, the term "active controls" itself should be discussed. In the broadest sense it refers to any control system that utilizes a sensor to detect deviations from some desired flight condition and which causes through a servo feedback mechanism an action of a device to bring the errant condition back to that desired. In that sense, active controls have been in use for over sixty years, starting with simple forms of autopilots that maintained a desired heading and altitude, and progressing to systems used to control "rigid body" aircraft dynamics. It was not until the sixties and early seventies however that systems were seriously considered for controlling aircraft elastic modes (refs. 1-12, for example). The term "active controls" is now generally considered by aeroelasticians to cover systems that are designed to produce performance and/or stability and structural response improvements through six control functions:

(1) Stability Augmentation (SA) - or Relaxed Static Stability (RSS) - a technique for eliminating the requirement for inherent aircraft static and dynamic stability by augmenting the stability with an active control system to a level that provides desirable handling qualities, improves maneuvering performance, and/or reduces aircraft weight by permitting a smaller empennage.

(2) Maneuver Load Control (MLC) - a method for redistributing wing lift and reducing drag during maneuvering flight. Incremental stresses may be reduced by deflecting wing control surfaces symmetrically in response to load factor commands in a manner that shifts the wing center of lift inboard, thus reducing wing root bending moments.

(3) Ride Quality Control (RQC) - a technique for improving crew and passenger ride comfort by reducing objectionable rigid body and structural vibrations through control surface deflections.

(4) Gust Load Alleviation (GLA) - a technique for reducing airframe transient loads resulting from gust disturbances. It encompasses control of rigid body and/or structural flexibility components of the airplane gust response.

(5) Fatigue Reduction (FR) - a technique for reducing fatigue damage rate by using active controls to reduce the amplitude and/or number of transient bending cycles to which the structure is subjected during turbulence or other vibratory input. This function is closely akin to MLC, RC, and GLA and may, in fact, be a derived benefit of the other functions.

(6) Flutter Mode Control (FMC) or Flutter Suppression (FS) - a technique for actively damping flutter modes by using oscillating aerodynamic surfaces, providing potential weight savings and/or extending flutter placard speeds.

There were many early analytical, and some experimental studies of the feasibility and potential benefits of many of these concepts although much of the emphasis was on gust load or motion alleviation. Reference 13 contains a bibliography of gust alleviation studies in the forties and early fifties. With a few notable exceptions (refs. 13-18, for example) it was not until the late sixties and early seventies that wind-tunnel and flight test verification of the various concepts began in earnest. These, and more recent tests, will be reviewed briefly relative to the scope of the tests and the results. Then the anticipated use of active controls on current and near future research and demonstration aircraft will be discussed. Finally, from the perspective of this review the "holes" remaining in the feasibility/benefits demonstration of active controls technology will be postulated. The focus will be on active control functions that are significantly impacted by the flexibility of the structure although so-called rigid-body functions also will be addressed briefly since the distinction between the two areas often is blurred.

WIND TUNNEL STUDIES

Some early wind-tunnel studies dealt with novel aero-mechanical active control concepts primarily intended for alleviation of rigid body motions due to gusts (refs. 13 and 18, for example). For direct response measurements dynamically scaled models must be used, and when structural flexibility is significant, the models also must be elastically scaled. Dynamic and aeroelastic wind-tunnel models have played an important role in the development of aircraft and spacecraft technology. Such models are used to obtain results at conditions where analytical results are known to be inaccurate as, for example, at transonic speeds and under separated flow conditions. Ordinarily, model results can be obtained in a more timely manner than flight results and, in fact, are used to minimize flight test requirements and to increase the safety of flight test. Also, model tests are more amenable to conducting extensive parametric studies than are flight tests. However, new technology and advanced concepts for aerospace vehicles that are continually being developed offer new challenges to modeling technology. The addition of active controls to models certainly added a new complexity to modeling technology and required the development of new lightweight miniaturized actuation systems and new testing technology. Great strides have been made in these areas. Still, such models cannot precisely simulate all aspects of the aircraft flight conditions. For example, there is always the background uncertainty of tunnel wall effects and resonances, and the difficulty of simulating maneuvering and atmospheric turbulence conditions. Thus there is the need for collateral flight test evaluation. The following review of wind tunnel studies, based on a literature search and the author's personal knowledge, is not considered to be exhaustive, but rather should be viewed as a representative sampling of some of the more significant relatively "basic" studies, and those associated with specific aircraft configurations.

Cropped-Tip Delta-Planform Research Wing

Paradoxically, the first practical successful wind tunnel demonstration of the feasibility and benefits of active control technology for elastic mode control was for the control function most difficult and potentially hazardous to achieve - flutter suppression. The cropped tip delta planform model (a simplified version of a supersonic transport wing) with leading and trailing edge active controls (shown in figure 1) was tested, beginning in 1972, in the NASA Langley Research Center Transonic Dynamics Tunnel (TDT) (ref. 19). Three control laws based on the "aerodynamic energy method" (ref. 20) were evaluated. Aside from demonstrating increases in flutter dynamic pressure due to operation of the Flutter Suppression System (FSS) of a minimum of 12 to 30 percent (figure 2--the broken caps on the bars for control laws B and C indicate the tests were terminated for load considerations before flutter as encountered), a major contribution of this study was the development of miniature hydraulic actuators which paved the way for future wind tunnel tests of actively controlled dynamically scaled aeroelastic models.

B-52 Control Configured Vehicle (CCV)

In another pioneer wind tunnel study of the use of active controls that was coordinated with flight tests of the B-52 CCV research aircraft (ref. 21), a 1/30-sized dynamically scaled aeroelastic model on a cable mount system was used to demonstrate the effectiveness of a flutter mode control (FMC) system and a ride quality control (RQC) system, and to obtain data for correlation with analysis and airplane flight results (refs. 22 and 23). The FMC system used actively controlled flaperons and outboard ailerons. A pair of fuselage-mounted horizontal canard surfaces were used for the RQC system. Figure 3 shows the model mounted in the NASA TDT and figures 4(a) and 4(b) present some of the results of the flutter suppression study which show that the analysis was conservative by about 10 percent when compared to the model flutter velocity and, although not shown here, calculated flutter speeds for the airplane were 8.3 percent conservative relative to the flight test; that both the model and airplane have the same closed-loop damping trends; and that in both cases the closed-loop system significantly increases the damping near the open-loop flutter velocity. Although there were some differences in damping level, the correlation between model and airplane data was considered good. The objectives of the RQC studies were to demonstrate the effectiveness of a ride control system in reducing the acceleration at the pilots station due to atmospheric turbulence. The RQC studies were conducted independently of the FMC studies. The simulated atmospheric turbulence was provided by oscillating vanes in the tunnel and by oscillating the model canard surfaces.

The results for a canard frequency sweep are shown in figure 5 for both the open- and closed-loop conditions in terms of the ratio of pilot station acceleration $\ddot{Z}_{nose}$ to canard command signal $\delta_{c,c}$ as a function of canard frequency. The reduction in response with the RQC system on is obvious. However, the reduction in the response due to excitation with the wind tunnel vanes was not as dramatic.

Variable-Sweep Fighter Wing

A study of the use of active controls to suppress flutter of a wing with an externally mounted store was conducted with a subsonic wind tunnel model in the flutter tunnel of the Eidgenossiches Flugzeugwerk in Emmen, Germany in 1973. (ref. 24). The control system drove a vane, attached to a store, which was controlled by a feed-back signal in a way so that it counteracted the store motion. The scheme is shown in figure 6. The study showed that the method was effective in increasing the damping of the relatively mild flutter mode involving the store. Figure 7 taken from reference 24 is a sample of the results which show a comparison of measured and calculated damping values for a configuration with 45° sweep angle. The analysis underestimates the tunnel flutter speed by about 10 percent (flutter suppression system off) and gives the same damping trend (FSS off and on).

Subsonic Rectangular Research Wing

Another flutter suppression study, reported in 1976 (ref. 25) and conducted by ONERA, France, utilized a wall-mounted rectangular wing of aspect ratio 5.3 and 12 percent thickness ratio. A large tank was fixed beneath the wing at 45 percent span. The aerodynamic control forces were generated by an aileron, controlled by a miniature servo using a signal generated by the movement of the wing. A single control law was used for the tested speed range of 0 to 88 meters per second. An increase of more than 15 percent was obtained for the critical flutter speed. Difficulty was encountered in pre-determining the control law. The best control law was obtained by manual adjustment carried out in the wind tunnel. Manual adjustment was possible only because there existed only one phase control and one gain control.

Complete Variable-Sweep-Wing Fighter Model Empennage

Suppression of empennage flutter was demonstrated in wind-tunnel tests by Messerschmitt-Bolkow-Blohm GmbH, Germany using a dynamically scaled "free flying" complete model mounted on a vertical rod that allowed simulation of "rigid body" motions (figure 8) (ref. 26). The flutter mode, which was characterized by large contributions of fuselage torsional movement was suppressed by a hydraulically driven rudder. The high torsional inertia forces (relative to the unsteady aerodynamic forces) lead to a mild onset of flutter with slow phase changes near the flutter point which simplified the flutter suppression task. Figure 9 is a sample of the results which shows the flutter speed versus damping for the stabilized and unstabilized system and the comparison with the analytical prediction for the unstabilized system. The analysis is seen to be about 5-percent unconservative.

C-5A Airplane Model

A form of load alleviation by means of active controls was demonstrated in wind tunnel tests of a 1/22-size aeroelastic model of the C-5A transport airplane. The purposes of the study were to demonstrate the benefits of the ALDCS (Active Lift Distribution Control System), develop test techniques, and provide data for correlation with analysis and flight test results (refs. 23 and 27, for example). The ALDCS was designed to reduce the incremental inboard-wing stresses experienced during gusts and flight maneuvers. Figure 10 shows the model mounted in the NASA Langley Research Center TDT. The model and the active control systems appeared reasonably representative of the airplane and the model ALDCS achieved its design goal in reducing wing bending moment. Figure 11 is a sample of the results showing the reduction in loads due to the ALDCS.

Aeroelastic Research Wing (ARW-1)

A large semi span flutter model with active trailing edge controls (Fig. 12) which was originally built to support the NASA DAST (Drones for Aerodynamic and Structural Testing) flight program (see section, Flight Studies) was used in a study in the TDT to test the relative capabilities of two different control laws to achieve a 44-percent increase in flutter dynamic pressure (ref. 28). One control law was based on the aerodynamic energy method and the other was based on the results of optimal control theory. At Mach 0.95, a 44-percent increase in flutter dynamic pressure was achieved with both control laws, thereby validating the two synthesis methodologies. Experimental results indicated that the performance of the systems was not as good as that predicted by analysis. The results also indicated that wind-tunnel turbulence is an important factor in both control law synthesis and experimental demonstration.

DC-10 Derivative Wing With Engine

A 4.5-percent scale aeroelastic model wing of a DC-10 derivative was tested to confirm the effectiveness of active controls to suppress critical flutter modes at speeds above passive flutter and to assess the accuracy of dynamic analysis methods applied to the active control functions of flutter suppression and gust load alleviation. A semispan version was tested in the Douglas low-speed tunnel (ref. 29) and a full-span complete model was tested in the Northrop Aircraft Company 7 x 10 foot low-speed tunnel (ref. 30). The model is shown in figure 13(a) and 13(b). Several different control laws were investigated including laws developed by Douglas based on classical methods and laws developed by the NASA Langley Research Center based on aerodynamic energy and optimal control methods. The tests were made for a range of fuel loadings and tunnel velocities. Figure 13(c) is an example of some of the results of the flutter suppression study. For gust-alleviation tests, a canvas banner was stretched across the tunnel upstream of the test section to provide the necessary turbulence. Some of the conclusions from these studies were:

1. The ability to increase flutter speed of the first critical flutter mode by using a relatively simple control system and control law was

demonstrated on both models. For the semispan model, the flutter speed for the critical 10-percent fuel condition was increased in excess of 25-percent over the passive flutter speed; for the full-span model, the first critical flutter mode (12 Hz) was suppressed entirely. A second flutter mode (23 Hz) became unstable for the full-span model at speeds above the passive flutter speed for the basic 12-Hz mode, and an attempt to control this mode using a notch filter was unsuccessful. Also unsuccessful was an attempt to suppress a flutter mode that crossed sharply into the unstable region, as induced on the full-span model by adding weights behind the wing tips.

2. The active control system also was able, for the most part, to reduce significantly the gust loads caused by turbulence induced in the tunnel. There was one notable exception: contrary to analytical predictions, the active system actually increased the structural loads caused by short-period motion of the full-span model. This was believed to be the result of the effects of the model support system, which was not accounted for in the analyses.

3. For the flutter tests,the agreement between the analytical predictions and the mode shapes, frequencies, damping values, and transfer functions measured in the tests was generally good. For the gust load alleviation test, the relative change in model response to turbulence was in agreement with analysis for the semispan model, but not for the full-span model. This was partly because of the simplistic model used to describe the turbulence field. The usual one-dimensional model of the turbulence gave predictions of higher gust loads than occurred. The predictions were better when a two-dimensional model was used, but were still not completely satisfactory.

4. The use of correction factors to account for control surface effectiveness and for measured phase differences in the experimental system resulted in good correlation between measured and predicted flutter boundaries as a function of gain and phase.

5. The wing "tip" feedback accelerometers had to be judiciously relocated inboard to prevent destabilizing the third wing bending mode.

F-16 Flutter Suppression Model

To support the F-16 aircraft flutter clearance program a 1/4-scale complete airplane model was designed by General Dynamics under Air Force contract for testing in the NASA Langley Research Center TDT on either a cable mount or sting mount system. The model was tested with many combinations of external stores without flutter suppression to obtain flutter boundaries. With a number of flutter conditions available from previous flutter clearance tests of the model, it was a logical choice for demonstration of active flutter suppression (ref. 31). A duplicate set of wings which permitted the use of the "flaperon" as an active control surface, and an on-board miniature hydraulic control system were required for the flutter suppression model. The model is shown mounted in the TDT in figure 14. Flutter suppression studies were conducted in two tunnel entries - in January, 1979 and in October, 1981. The objectives of the F-16 flutter suppression program were to develop the technology and to increase the credibility of using active controls to suppress wing/store flutter on a flight test demonstration aircraft and/or an operational aircraft. The second series of tests essentially resolved anomalies or questions encountered in the first tests and also demonstrated flutter suppression for two external store configurations - one exhibiting symmetric flutter and the other exhibiting antisymmetric flutter. Also the FSS was evaluated for the case of a simulated actuator failure. The test showed that for the configuration studied, the flutter mode could be controlled with an operational actuator on only one side.

YF-17 Flutter Suppression Model

The unique model shown in figure 15 has been used in several studies in the NASA Langley TDT since September, 1979 to generate much useful information on suppression of wing/store flutter with active controls. The Northrop built semi-span 30-percent scale flutter model, simulating the YF-17 airplane, is sidewall-mounted on a system of bars and cables that allows the flexible half-fuselage to pitch and plunge. It is "flown" by a "pilot" in the tunnel control room. In early tests the model was used to gain experience in developing test techniques and control law implementation, and to evaluate several conceptually different control laws (refs. 32 and 33, for example). The test featured a store configuration that was intentionally designed to exhibit a violent flutter condition. During this program, the British Aerospace Corporation, MBB, Northrop, ONERA, the Air Force FDL, Technion, Israel, and NASA cooperated in deriving control laws to suppress the flutter. The model was tested up to 170 percent of the open loop flutter dynamic pressure in a number of cases, with the indication that a substantially greater improvement was achievable.

The FSS tested in this study used an analog computer as had most model flutter suppression systems studied previously. Anticipating the feasibility of using adaptive control methods (which would require the use of a digital computer controller) a later series of tests were conducted in which control laws that previously were implemented using an analog computer were implemented with a digital computer (ref. 34). The constant Mach Number data in figure 15 show how damping in the flutter mode decreased as dynamic pressure was increased for the cases of inactive (open loop) and active (closed loop) flutter suppression system with the same control law implemented first by an analog computer and then by a digital computer. It can be seen that the digital data agree very well with the analog data and that in both cases the projected flutter dynamic pressure is about twice the value projected for the open-loop condition.

The tip missile and cable system shown in the photo in figure 15 was used to demonstrate the effectiveness of an adaptive active control system in suppressing flutter when the model transitions from a stable configuration (with tip missile) to an unstable one (tip missile ejected). The missile was ejected at a tunnel flow condition that was above the flutter boundary for the wing without the tip missile. When the missile was ejected, the wing began to flutter. The digital computer first sensed that the wing oscillatory motion had become unstable, then activated a control law and stabilized the motion.

Tornado Active Flutter Suppression and Gust Load Alleviation Model

An existing low speed flutter model of the Tornado fighter has been equipped with active controls for studies of active flutter suppression and gust load alleviation in a cooperative test program by ONERA (France), the RAE and BAC (United Kingdom), and NLR (Netherlands), and the DFVLR and MBB (Germany). The author is not aware of the details of the model. Flutter suppression control laws designed by each of the participating countries are being evaluated with the model as was done earlier with the YF-17 model. The model was tested at the Göttingen low speed tunnel for flutter suppression and in late 1983 gust response measurements were made. Gust alleviation studies are planned for the summer of 1984.

X-29A Simulation

In a recent unusual study of "body-freedom-flutter" on a forward-swept-wing configuration (a simplified aeroelastic model of the X-29A demonstrator) in the NASA Langley TDT a stability augmentation system (SAS) which employed an active canard was used to stabilize the model with negative stability margins of up to -25-percent. The 0.5-scale semispan flutter model (Fig. 16), which simulated the early X-29A design, used a mount system similar to that used in the YF-17 flutter suppression studies, so that pitching and vertical translation degrees of freedom were provided. The purposes of the study were to investigate the "body-freedom-flutter" phenomenon (a coupling of wing-bending and airplane pitching modes) using a realistic forward-swept-wing configuration in the flutter critical transonic speed regime, and to ascertain the ability of existing analytical tools to predict its occurrence. Although evaluation of the airplane reduced static stability augmentation system was not an objective of the study, it was necessary to have such a system in the model because of the desire to simulate the interaction of the fuselage pitching characteristics (influenced by the SAS) with the wing flexible modes. Aside from the flutter information derived from the tests, additional experience was gained in the implementation of active controls in model studies.

Tilt-Rotor Research Model

During the period 1972-1978 a study was undertaken at the Massachusetts Institute of Technology under NASA sponsorship to investigate the alleviation of the effects of gusts on tilt-rotor aircraft by means of active control systems (reference 35). The study included the development of a novel gust generator, derivation of the equations of motion of the rotor-wing combination, the design of various gust alleviating active control systems, and the testing and evaluation of these control systems by means of wind tunnel model tests. The model was a semi-span unpowered, three-bladed tilt-rotor with a diameter of 33.75 inches. A closed loop proportional control system was provided for collective pitch and two orthogonal components of cyclic pitch. The objective was to evaluate improvement in wing bending and rotor flaping responses to sinusoidal gust inputs that could be obtained through the use of feedback control loops. It was concluded from the tests that a 25-percent higher feedback loop gain was required to achieve a given reduction in the rms level of wing vertical bending moment than was predicted analytically but that generally reductions of wing vertical bending response of approximately 30-percent were achievable with simple feedback systems feeding wing vertical bending motion to the rotor longitudinal cyclic control. A predicted destabilizing effect upon the wing torsion mode of feeding back wing vertical bending velocity to the rotor longitudinal cyclic pitch was not observed in the tests. Rotor flapping response data obtained from the tests were inconclusive due to rotor unbalance effects.

Helicopter Rotor Vibration

To complete this review of wind-tunnel studies of active controls applications, mention should be made of the reduction of helicopter rotor vibrations. This application could be considered to fall under the third category (Ride Quality Control) or the fifth category (Fatigue Reduction) of the six control functions listed in the Introduction. A primary source of the severe vibration problem that plagues helicopters is the unsteady (nearly periodic) airloads caused by blade rotation, the harmonics of which may be transmitted to the fuselage. Active control for vibration suppression on helicopters, known as Higher Harmonic Control (HHC) or Multicyclic Control has been studied on a variety of models in "open-loop" tests (refs. 36 and 37, for example). Closed-loop studies also have been studied in the NASA Langley Research Center TDT (ref. 38) and in the Boeing Vertol V/STOL Wind Tunnel (ref. 39). In the concept studied in these tests, the rotor blade vibratory forces and moments which cause airframe vibration are altered, at their source, before they reach the airframe by super-imposing non-rotating swashplate motions at the blade passage frequency (four per rev for a 4-bladed rotor) upon the basic collective and cyclic flight control inputs. The amplitude and phase of the higher harmonic inputs are chosen to achieve minimization of the responses being controlled, i.e. vibratory acceleration levels at the pilot station. The control concept and the model used in the Langley TDT tests are shown in figure 17 along with a qualitative sample of the results. The four-bladed articulated rotor system used in this investigation carried blades that were dynamically scaled to be representative of a current generation rotor system. The rotor system was mounted on the ARES (Aeroelastic Rotor Experimental System) test bed. The ARES rotor shaft is belt driven by a variable speed electric motor. The rotor control system is a conventional swashplate system which is remotely controlled through the use of three electronic servos and hydraulic actuators. The control system has the high frequency response characteristics needed for higher harmonic inputs. This test was the first time that an adaptive control system employing optimal control theory had been used for helicopter vibration reduction. The test was successful in that the control algorithms functioned flawlessly and significant reductions in vibratory response were achieved (70-to 90-percent over the range of advance ratios tested). The test results also indicate that HHC can lead to increases in blade and control system loads so that this fact must be considered in any flight test demonstration of the HHC concept. As a matter of fact, this wind-tunnel study has led to a flight test program which will be discussed later. The primary results of the TDT tests were confirmed in the Boeing Vertol tests which were done for a different rotor system. This model rotor was a 10-foot diameter, four-bladed, soft-in-plane hingeless configuration. The blades were dynamically scaled to an early version of the Boeing Vertol model 179 helicopter.

SUMMARY OF WIND-TUNNEL STUDIES

A review of the wind-tunnel active control studies surveyed here shows that initial objectives were to demonstrate the feasibility of active control concepts and to assess their effectiveness. Later studies began to deal with "engineering" aspects such as the effect of failed actuators and the effects of switching from analog to digital computers. The level of sophistication rose with the studies of adaptive concepts. Throughout all these studies modeling capabilities, testing techniques, and data analysis methods were being developed. A common thread running through most of the studies was the finding that the vagaries of working with actual hardware with the attendant friction, mechanical lags and control effectiveness discrepancies, and possibly tunnel wall effects, turbulence, and resonances dictated that control law gain and phase settings had to be established or adjusted during the actual testing. Most of the studies were concerned with the most hazardous of the active control functions, flutter suppression, which could be demonstrated directly in terms of system-on/system-off structural stability. The maneuver and gust load alleviation studies, where the static or low frequency aerodynamic effects are more important, and where correct aerodynamic simulation is more difficult (due to model size relative to the test section, and limited atmospheric turbulence or maneuvering aerodynamics simulation capability) rely on more circumspect methods of evaluation of benefits such as changes in transfer functions. In all cases the active control functions were tested individually rather than as part of an integrated system.

FLIGHT STUDIES

"Rigid-Body" Control Functions

Before addressing flight studies of active controls that fall under one or more of the six control functions identified in the Introduction as being those in which the airframe elasticity can play a dominant or significant role and which are collectively the focus of this paper, mention should be made of flight studies of functions or concepts that aeroelasticians would consider peripheral to "the active controls technology area" but which may be considered by controls people to be "active". Basic to nearly all control functions involving response sensors, feedback mechanisms, and control laws is the "fly-by-wire" (FBW) concept, in which the pilot-operated controls are connected to the control surfaces by means of an electrical system rather than mechanical linkages. In the early seventies both the U. S. Air Force, the NASA, and others used flight tests to demonstrate the reliability and effectiveness of the fly-by-wire concept. An Air Force study used a YF-4E test aircraft to demonstrate the Survivable Flight Control System (SFCS), a quadruply redundant, dispersed, three-axis, analog FBW primary flight control system (ref. 40). The feasibility of using digital fly-by-wire systems to control aircraft was demonstrated in a NASA study by the development and flight testing of a single-channel system using Apollo hardware in an F-8C test airplane (ref. 41). This was the first airplane to fly with a digital FBW system as its primary means of control and with no mechanical reversion capability. (A triple channel analog backup was used.) The system was later expanded to a triple channel system which was used to evaluate certain aspects of the system used on the Space Shuttle Orbiter. Another early study of the FBW concept, which made use of a modified Mirage III fighter airplane, uncovered several problems that had to be addressed (ref. 42). These early FBW studies increased confidence in the safety and reliability of using computer-controlled electronic control systems that form the basis for active control systems. With the benefits of FBW systems becoming more apparent a need was seen for the development of an integrated flight control system that would have the capability of providing the level of control required for aircraft with nonlinear and complicated control problems (such as STOL and VTOL aircraft). Consequently, a flight control concept called TAFCOS (Total Automatic Flight Control System) was developed and demonstrated on a DHC-6 Twin Otter aircraft (ref. 43). The fundamental idea in the design of TAFCOS was to make maximum use of a priori knowledge of the vehicle characteristics and to build that information into a controller structure that permits flight path control of the vehicle over the entire flight envelope, without the need for complex mode-switching logic. The main objective of the flight test was to verify that the TAFCOS architecture was suitable for use in a typical digital flight control system and that the computational structure had the ability to cope with a real world environment.

Some of the "peripheral" active control systems alluded to earlier include those designed to provide for direct lift and side force capability for better maneuverability, target tracking, and evasive maneuvers; for automatic configuration control such as maneuver flap deployment, wing variable sweep, engine inlet/nozzle control, etc., for increased maneuverability and performance; and for envelope limiting functions (angle of attack, normal load factor, yaw angle, roll rate, etc.) for increased safety and "care-free" flying qualities. Many of these concepts have not only been studied in flight tests but are in operational use. Reference 44 presents a good summary of Air Force sponsored flight studies in these areas (and also includes some tests dealing with structural response). These studies included the PACT/CCV F-4, the variable stability NT-33A, the CCV YF-16, the AD-7D Digital Multimode Flight Control System (DMFCS), the F-15 Integrated Flight and Fire Control (IFFC), and the AFTI-16 programs.

The PACT (Precision Aircraft Control Technology) Program (ref. 45) modified the SFCS F-4 aerodynamic configuration by the addition of two close-coupled horizontal canard surfaces just forward of the wing root leading edge. The canards moved the aerodynamic neutral point forward and caused the unaugmented aircraft to be longitudinally unstable subsonically. This permitted the investigation of maneuvering performance improvements achievable through the application of the relaxed static stability concept. This flight test program demonstrated maneuvering performance improvements over the basic F-4 and allowed investigation of some aspects of direct force control (DFC). Other early studies of DFC utilized the variable stability NT-33A aircraft which obtained its direct side force control by deflection of the rudder to cancel the yawing moment resulting from the asymmetric drag of wing tip tank "petals" (ref. 46). Although the maximum side force available produced only 0.17 lateral "g" it was concluded that the DFC concept was worthy of further study.

The Control Configured Vehicle (CCV) YF-16 program flight-demonstrated seven decoupled control modes attainable through direct lift control and direct side force control, by means of nine movable surfaces which included flaperons, vertical canards and trailing edge flaps (ref. 47). Like most research efforts, this program surfaced as many new questions as it answered.

The flight tests showed a clear need to tailor specifically the authorities and response characteristics of each control mode to the task being performed.

While the CCV YF-16 program was focused on decoupled control modes, an A-7D aircraft was used to explore the benefits available from conventional task-tailored multimodes incorporated through a digital command augmentation system. Two multimode control laws (Flight Path and Precision Attitude) were tailored to increase pilot effectiveness in accomplishing air-to-air and air-to-ground weapons delivery tasks (ref. 48). The results of the 56-flight program showed that significant weapon delivery performance improvements were possible, even though only conventional control surfaces were utilized.

Another step in the direction of multimode applications and integrated control concepts is the Air Force Integrated Flight and Fire Control (IFFC)-1/Firefly III program which uses a production F-15 test bed. The IFFC design involves the blending of the flight control, director fire control, and weapons system technologies together with the pilots abilities to enhance weapon delivery accuracy and survivability. In this effort no attempt was made to redesign completely the F-15 flight or fire control system, but rather emphasis was placed on staying within the physical and functional limitations of the F-15 baseline systems. The success of the F-15 IFFC system design is determined by scoring live gunnery and inert bombing tasks against realistic targets (ref. 49). The results of flight tests completed as of December 1981, in which all of the systems were operated, provide a high degree of confidence that the program goals of improved weapon delivery accuracy will be achieved.

The AFTI/F-16 program extends and integrates into a single F-16 test aircraft most of the fighter technologies that were investigated individually under the previously described programs. The AFTI-16 aircraft (an F-16 modified by the addition of a dorsal fairing and forward-mounted "vertical" canards as on the CCV F-16; by provision for shifting the c.g. by fuel management for relaxed static stability tests; and by replacement of the analog flight control system with a digital system) ties together the decoupled control capability provided by direct-force control with an integrated flight/fire control system, all implemented through a task-tailored triplex multimode Digital Flight Control System (DFCS) (ref. 50). The primary objectives of the flight tests were to demonstrate and validate the triplex DFCS and to demonstrate improved mission performance and effectiveness. Initial results indicate the DFCS works well, is reliable, and exhibits a 10-fold increase over analog control law processing capability. It is worth mentioning that the basic F-16 fighter is the first production aircraft to incorporate an active control system from its inception (ref. 51). The flight control features are a quadruplex analog fly-by-wire system with fail-operative/fail-operative redundancy, three-axis stability and command augmentation, relaxed static stability, automatic angle of attack and normal acceleration limiting, and automatic full-span leading-edge maneuvering flap. The analog system will be replaced by a digital FBW system in production aircraft starting in late 1986.

An interesting approach for obtaining fighter active control technology design data involves flight tests of a remotely piloted research vehicle (RPRV) with active controls to validate highly maneuverable aircraft technologies (HIMAT) (ref. 52). The HIMAT RPRV is a sub-scale closely coupled canard-wing vehicle which includes a digital active control system for controlling relaxed static stability and direct force control functions. The operational goal of an 8-g sustained turn capability at Mach 0.9 at an altitude of 7620 meters coupled with nonlinearities in the configurations aerodynamics caused greater-than-expected negative stability margins (-30 percent) for some high angle-of-attack flight conditions and low Mach numbers so that an angle-of-attack limiter was required. Also, flexibility effects caused negative directional stability for small angles of sideslip so that special provisions to prevent triming to non-zero angles of sideslip had to be added to the relaxed directional static stability system.

Before leaving this discussion of some of the more significant flight studies of "rigid body" active control functions, it seems appropriate to mention the Space Shuttle which is operating with what is probably the most elaborate digital fly-by-wire flight control system (FCS) in use to date (see ref. 53, for example). In residence in each of four redundant general purpose computers (GPC's) at lift-off are the guidance, navigation, and control algorithms for the entire flight. (A fifth GPC houses a backup FCS.) The FCS must perform the functions to fly the Shuttle as a boost vehicle, as a spacecraft, as a reentry vehicle, and as a conventional aircraft. The crew is provided with both manual and automatic modes of operations in all flight phases including touchdown and roll out. The vehicle requires augmented stability in both pitch and yaw over a large percentage of the flight envelope. Control forces are generated by gimbaled rocket thrusters, reaction jets, and/or aerodynamic surfaces. During regions of high dynamic pressure,, a load relief system in both pitch and yaw minimizes air loads on the vehicle. The system shapes the trajectory, performs in-orbit navigation chores, sets proper attitude during atmospheric entry, controls the energy state during landing approach, and is capable of a completely automated landing with the exception of gear extension and braking.

It is worth noting that the space effort has led the way in the use of flight-safety critical active control concepts - the Shuttle being the current example. It was the success of the Apollo control system that encouraged the early studies of direct fly-by-wire control systems for aircraft. The ensuing progression of flight studies over the past decade has laid the ground work for the increasing use of active controls in operational aircraft for controlling flight path, thrust, altitude, stability, and configuration.

Although the preceding discussion on "rigid body" control functions has been relatively wide-ranging it has been primarily focused on efforts that were oriented to new technology demonstration that formed the basis for future utilization. It by no means covered the entire spectrum of fly-by-wire (FBV) applications. Figure 18 from reference 54 gives a hint of the full scope of FBW applications without distinguishing between FBW applications for "rigid-body" control functions and those designed to control structural response or increase stability. Indeed, this distinction becomes blurred for many of the FBW applications. Rediess points out in reference 49 that although the chart emphasizes U. S. aircraft, several key developments in Europe are included, several of which are briefly described. For example, the Concord is described as representing the first, and as yet only, high authority Stability Augmentation System (SAS)/ Control Augmentation System (CAS) in commercial transports. The Swedish SAAB-Scania JA-37 has a fully operational single channel full authority digital automatic Flight Control

System (FCS) with mechanical reversion. The Airbus A310 has mechanical primary controls, direct FBW spoilers, and a digital autopilot. (The A-320 will have Quad DFBW with dissimilar redundacy hardware and software with relaxed static stability capability, but with rudder and pitch trim mechanical back-up). The multinational Tornado fighter is operational with an analog command/stability augmentation system with a dual digital autopilot and mechanical reversion for the ailerons. The French Mirage 2000/4000 have flight critical analog FBW, digital autopilot, and no mechanical reversion. The Mirage 4000 features relaxed static stability and automatic variable camber. Under development is the Swedish SAAB-Scania JAS-39 fighter with a flight critical triplex DFBW flight control system and the Israeli IAA Lavi with a triplex DFBW system with RSS which includes an analog back up system.

Many of the latest currently operational fighter aircraft make extensive use of fly-by-wire active control functions for configuration control to increase performance. For example, the F-14 central air data computer is used to position automatically several surfaces for optimum performance and load reduction (ref. 55). These include the variable sweep wing, maneuver flaps, auxiliary flaps, leading edge slats, spoilers, differential horizontal tail, and an extensible glove vane.

Flight Studies of Control Functions Involving Significant Aeroelastic Response or Stability

Aeroelastic deformations affect not only basic flight characteristics such as performance, handling, controllability, and ride qualities; they also increase structural loads and fatigue, and can cause structural instabilities, divergence and flutter. In the quest for increased performance and fuel efficiency, aircraft design is tending toward long flexible wings, thin control surfaces, and marginal or negative static stability. As discussed earlier very sophisticated automatic flight control systems are being developed to improve stability and damping, and to increase efficiency and controllability. As stated in the Introduction, similar systems are being advocated and developed for modal suppression to alleviate gust loads, improve fatigue life, improve vehicle ride quality, lessen maneuver loads, prevent divergence, and to suppress flutter. As I. E. Garrick pointed out in his 1976 Von Karman lecture (ref. 56) a major trend which will play a dominant role in research, development, and practice in the years ahead is the union of modern control technology and aeroelasticity. Although aeroelasticians and control specialists have in the past usually gone their separate ways, and both fields have become quite sophisticated, in the last few years there have been attempts at real cooperation and adapting to each other's methods. One might ask why is this trend occurring now? After all, active control concepts are not new. In the 1950 Wright Brothers Lecture, Bollay (ref. 57) gave a comprehensive outlook on the field, and a 29-year old textbook (ref. 58) speaks of the possibility of flutter suppression by means of closed-loop automatic control. Also, a gust alleviation system that was designed to reduce wing bending loads by operating the ailerons symmetrically in response to signals from a nose-mounted gust vane was flown in an Avro Lancaster airplane (ref. 14) in 1952, but with questionable success. (The measured alleviation was much smaller than expected and the airplane suffered a considerable loss of stability due to the large pitching moment contributed by the ailerons and airframe flexibility.) Also, in the early fifties flight tests were conducted on a C-47 transport (under Air Force sponsorship) of a Douglas Aircraft Company concept for gust load alleviation that used mechanical sensing of wing deflection to activate alterons to reduce the loads (ref. 16). Tests in the late fifties of an automatic gust alleviation system on a C-47 transport which utilized a nose boom mounted vane to sense the gusts and wing trailing edge flaps and horizontal tail elevators to reduce airplane motions used an electronic interface between the sensor vane and the control actuators (refs. 15 and 17). The answer to the question of why now the growing interplay between aeroelasticians and control specialists resides partly in design trends which are emphasizing high performance and wide mission requirements and thus in the need to avoid many inherent compromises; partly in improved hardware; but mostly it is the growth of confidence in the concepts and methods of active controls gained by their general use in the space program and, as discussed previously, in broad programs for certain research aircraft and in several military and civilian development areas.

The major flight tests and operational use of the active control concepts that involve significant structural response now will be discussed. They range from the early modal suppression flight studies using the B-52 airplane (aimed at gust and maneuver load alleviation) to more recent flutter suppression and helicopter vibration reduction studies.

B-52 Load Alleviation and Structural Mode Stabilization (LAMS)

The LAMS Program used a B-52 test bed to demonstrate the capabilities of an advanced flight control system to alleviate gust loads and to control structural modes on a large flexible aircraft using existing aerodynamic control surfaces as force producers (refs. 6, 11 and 44, for example). Figure 19 (ref. 44) shows that all available control surfaces were used in the LAMS system, and also depicts the gyros which provided structural mode rate signals to the flight control system. The two outboard spoiler panels were operated symmetrically around a 15° biased position, the ailerons were used both symmetrically and asymmetrically, and the elevator and rudder were used in the normal manner. The figure of merit for the LAMS system was the percent reduction in fatigue damage due to turbulence. Figure 20 presents the reductions in turbulence-induced fatigue damage rates obtained with the LAMS system. These data are based on test results at three flight conditions and include effects of vertical, lateral, and rolling gusts. For comparison purposes, a conventional baseline SAS (Stability Augmentation System) was implemented to control only rigid body motions. The LAMS system reduced the basic aircraft wing fatigue damage rate by about 50% and also significantly bettered the baseline SAS fatigue rate reductions. LAMS also demonstrated large improvements in fatigue damage rates at the mid-fuselage stations. Even more important than these quantitative results was the demonstration that a control system can be designed to alter significantly the structural response characteristics of an aircraft.

The LAMS Program indicated a limited ability to reduce acceleration at the pilot station using only existing aerodynamic control surfaces. And, because of the structural mode shapes it was evident the force had to be located near the point of desired effect. The need for force producers at the site of desired acceleration reductions was the basis of the Identical

Location of Accelerometer and Force (ILAF) concept to be discussed subsequently.

A direct lift control (DLC) study conducted during the LAMS Program also showed the desirability of uncoupling the rotational and translational degrees of aircraft motion (ref. 59). Spoilers and symmetrical ailerons were used with elevators to implement DLC. Flight test results showed that uncoupling pitch and heave through DLC greatly simplified the precise maneuvering required during aerial refueling and instrument approaches. The B-52 LAMS testbed had no means of obtaining direct sideforce control (DSFC).

The potential benefits available from decoupling the flight motions and from having force producers at critical locations led to a decision to reconfigure the LAMS B-52 control surface complement to more fully explore newly emerging ACT concepts.

B-52 Control Configured Vehicle (CCV) Program

The CCV B-52 flight control surfaces and the concepts they were used to implement are depicted in figure 21. The active controls functions were Flutter Mode Control (FMC), Maneuver Load Control (MLC), Ride Control (RC), Fatigue Reduction (FR), and Stability Augmentation (SA). Several new control surfaces were added to change from the LAMS to the CCV aerodynamic configuration. These include one vertical and two horizontal canards mounted on the forward fuselage at the pilot station, three segments of flaperons on each wing replacing the inboard flaps, and a new aileron located just outboard of the outboard flap on each wing. Standard flight control surfaces retained were elevator, rudder, five of seven spoiler segments, and the original ailerons. Also shown on figure 21 are the external fuel tanks which were adversely mass-balanced to create a relatively benign flutter mode within the level flight speed capabilities of the testbed. This was necessary to permit investigation of Flutter Mode Control on the normally flutter-free B-52. Dropping the tanks while in a flutter condition would immediately stabilize the flutter mode should the FMC system fail.

Of the five ACT concepts implemented on the CCV B-52, only Fatigue Reduction was common between the LAMS and CCV Programs. A slightly modified version of the LAMS system was included on the CCV B-52 to demonstrate compatibility of this concept with the other ACT systems. The objective of the Ride Control System was to reduce turbulence-induced accelerations at the pilot's station by 30% without increasing other fuselage accelerations by more than 5%. The goal for Maneuver Load Control was to reduce wing root bending moments by 10% of design limit during a 1-g incremental load factor pull up maneuver. The objective of the Stability Augmented System was to provide adequate aircraft flying qualities at centers-of-gravity as far aft as the neutral point. The goals of the Flutter Mode Control System were to increase the flutter placard speed by at least 30% and flight demonstrate flutter-free operation ten knots (18 km/hr) above the unaugmented flutter speed. Flight test results verified achievement of the CCV B-52 design goals and demonstrated compatibility of the five active controls functions (refs. 60, 61, 62). That is, the following systems were operated simultaneously: FMC, MLC, and FR; FMC, MLC, FR, and RC; FMC, SA, MLC, and FR. (See section of paper on wind tunnel tests for comparison of flight and wind tunnel results.)

XB-70 Structural Mode Control Program

This program was undertaken to develop the elastic mode control system called ILAF mentioned in the discussion of the B-52 LAMS program. The concept on which it is based was first developed in the analytical study reported in reference 4. The ILAF system flight-test program (ref. 63) was conducted to investigate the ILAF system concept rather than to develop an optimum operational system. No gust alleviation system was included and only control of the symmetric structural modes was attempted. To flight test the ILAF-system under well-controlled conditions an aerodynamic shaker system consisting of a pair of small horizontal oscillating vanes mounted on the nose of the aircraft was used. The configuration is shown in figure 22. (The ILAF force generators were the elevons shown shaded in the figure.) The shaker system was capable of exciting the first four symmetric modes. The flight test data were obtained with the B-70 normal flight augmentation control system (FACS) engaged. The flight investigation showed that the ILAF system encountered localized structural vibration problems requiring a revision of the compensating shaping network. However, successful structural mode control was obtained without adversely affecting the rigid body dynamics.

In general, the ILAF system was more effective at supersonic than subsonic flight conditions because the aerodynamic forces generated by control surface deflections in supersonic flight are concentrated at the control surfaces; thus the conditions for which the ILAF system was designed were more nearly satisfied. The ILAF system reduced the response of the first symmetric mode when elevon deflections were greater than $\pm 0.66°$ in subsonic flight and greater than $\pm 0.52°$ in supersonic flight.

The results of a turbulence encounter at a Mach number of 1.20 and an altitude of 9754 meters (32,000 feet) indicated that the ILAF system reduced vehicle response at this flight condition.

The results of an analytical study showed that the addition of a small canard to the modal suppression system would greatly improve the automatic control of the high frequency symmetric modes. Although this study showed the shaker-vane ILAF system to be effective in reducing the modal response, the B-70 airplane was taken off flight status before the system could be installed and tested.

YF-12A Structural Mode Excitation

The success of the B-52 and XB-70 programs resulted in several proposals for the application of CCV technology to the YF-12A aircraft, a large, flexible vehicle capable of flying in the subsonic, transonic, and supersonic flight regimes. A LAMS system was designed which utilized small canard vanes mounted on the forebody chine in conjunction with the outboard elevons (figure 23). However, budget and schedule constraints of the YF-12A program prevented implementation of the LAMS program. Ultimately the canards were installed as modal excitation vanes and a flight test program was undertaken to measure modal response at Mach numbers from 0.7 to 2.70 for comparison with NASTRAN calculations (ref. 64). The results allowed an evaluation of analytical methods in three different areas - structural modeling, structure/aerodynamic interconnection, and aerodynamic modeling. No LAMS testing was accomplished.

The NASTRAN structural model was found to describe adequately the dynamic behavior of the YF-12A aircraft. Aerodynamic forces were transformed to the structure by use of the surface spline in the NASTRAN program. This transformation gave reasonable lift distributions only when several splines were used to cover the planform. The linear spline transformation in COSMIC NASTRAN was found to give erroneous results. Aerodynamic methods which were found to give acceptable answers were the doublet lattice method, steady state doublet lattice with uniform lag, Mach box method, and piston theory - each method, of course, being applied only to the appropriate speed regime. These methods, carefully applied, were found to predict adequately the dynamic behavior of the YF-12A aircraft.

B-1 Structural Mode Control System (SMCS)

The B-1 is one of the first vehicles to include a control configured vehicle concept in the early design phase (ref. 65). The flexibility inherent in the vehicle, when combined with low-altitude turbulence, can produce an unacceptable acceleration environment at the crew station. To alleviate this environment the B-1 incorporates a SMCS whose main external feature is a set of vanes near the crew station which are canted down 30° from the horizontal as shown in figure 24. Since the B-1 has full structural integrity with or without the SMCS operating, a fail-safe approach using dual redundancy in the sensors, electronics and actuators was employed to permit centering of the vanes in case of system failure. Sensor inputs are derived from vertical and lateral accelerometers, with gains scheduled by dynamic pressure. Relatively simple control algorithms are used to generate commands the vane actuators.

Tradeoff studies indicated that 4,482 kg would have been added to the fuselage to meet ride quality requirements without SMCS. Since the SMCS weighs about 182 kg, active control permits a weight saving of some 4300 kg, a substantial benefit. Evaluation of the system performance in flight showed that the SMCS reduced both lateral and vertical load factors to the specified levels without degrading basic handling qualities.

C-5A Load Alleviation

Various load alleviation concepts have been considered and/or used on the C-5A transport airplane, progressing from a Maneuver Load Distribution Control System (MLDCS) to a Passive Lift Distribution Control System (PLDCS) to the currently operational Active Lift Distribution Control System (ALDCS). Reference 66 summarizes the use of these systems. The objective of the MLDCS development program was to reduce positive maximum wing root bending moments by 10-percent while minimizing effects on handling qualities and aircraft performance and utilizing existing hardware with a minimum of new components. The system used the existing pitch and yaw/lateral SAS computers to provide the means of introducing desired commands to the ailerons and pitch compensation inputs to the inboard elevators. The system affected only maneuver loads above a load factor of 1.5. Gust loads were not significantly affected due to both the high "g" onset-level and the limited frequency response range of the system. The flight test program evaluated handling qualities and provided substantiating data for structural load reductions.

The PLDCS was an interim measure designed to reduce the new hardware required in the MLDCS in order to obtain early fleet incorporation of a load reduction system and to provide service life improvement by reducing 1-g mean bending moments. This passive concept evolved into a fixed aileron uprig system with specific amounts of uprig as a function of airplane configuration and flight condition.

The latest C-5A load reduction system, ALDCS, has been in operational use with the entire C-5A fleet since 1975. Some of the objectives of the ALDCS are to reduce gust rms wing root bending moments by 30-percent while limiting gust rms wing root torsional moment increases to less than 5-percent, to reduce maneuver incremental wing root bending moment by 30-percent, and to provide a "full time-fail safe" system. A noteworthy aspect of this development effort was the use of a dynamically and elastically scaled model (discussed in the section on wind tunnel testing) which provided an experimental dynamic loads/flutter data acquisition tool with which to gain confidence in the analytical methods used in development of the ALDCS. The systems mechanization consists of an array of sensors, gains, and filters used with existing control effectors. The components of the system are shown in figure 25. The maneuver load relief function is accomplished by commanding the right and left ailerons symmetrically. Feedback sensors used are two vertical accelerometers per wing, both at an outer wing location. The signals from these accelerometers are averaged and compensated by smoothing filters that attenuate sensor noise and aid in the elimination of higher frequency wing vibration modes. Resulting control signals are gain scheduled by aircraft dynamic pressure from the Central Air Data Computer (CADC) to provide proper stability and load-relief schedules and to minimize handling qualities degrations throughout the aircraft speed envelope. Airplane pitch rate, obtained from the pitch Stability Augmentation System (SAS) rate gyro, is utilized to augment the airplane short period damping and thereby alleviate the excitation of short-period induced-gust loads and restore handling qualities degraded by aileron pitching moment effects. An existing C-5 autopilot subsystem vertical accelerometer mounted in the forward fuselage provides additional gust loads control and compensates the airplane pitch response characteristics.

Flight data, obtained by instrumenting 13 of the modified aircraft, closely followed the system analysis/design predictions. An example of flight test results is shown in figure 26. Maneuver and gust load incremental wing stresses were reduced by approximately 30-percent during normal operation and by some 20-percent during aerial refueling. Significant improvements in fatigue endurance are projected as a result of the ALDCS, with a conservative 1.25 life improvement factor now being used to track individual C-5 aircraft. System reliability, initially predicted to be 3,000 operational hours, actually resulted in a mean time between unscheduled component removals of about 1000 hours.

L-1011 Active Controls

Several active controls applications have been investigated for the L-1011 airplane. Some are in active use (refs. 67, 68). A Mach trim compensator senses Mach number changes and, when commanded by a computer, moves an actuator to reposition the stabilizer without any signal from the pilot. Flap load relievers sense airspeed and flap deflection, and a computer-actuator system regulates flap angle following a programmed schedule. A yaw damper and autoland system also are in use. It is noteworthy that the yaw damper has been shown through flight tests to significantly reduce vertical tail shear loads due to lateral gusts (ref. 69). Of more interest here however, are two "new technology" active control systems that have been flight verified on the L-1011 - a load relief system and a reduced static stability system. The test airplane configuration is depicted in figure 27. The load relief is effected by redistributing the wing aerodynamic center of pressure from outboard to inboard by means of symmetrical deflection of the ailerons. The active Aileron Control System functions to alleviate maneuver and gust loads. For the reduced static stability studies, the test airplane was equipped with Pitch Active Control System (PACS). It has an all-flying horizontal tail with mechanically geared elevators. The elevator was downrigged five degrees to compensate for the loss in nose-down control capability as the c.g. was moved aft to simulate relaxed stability conditions. Flight test results were encouraging. No difficulties were encountered in the load reduction tests, and measured responses agreed favorably with predictions. Emphasis during the relaxed static stability flight test program was placed on obtaining a thorough quantitative evaluation of airplane handling qualities at cruise conditions where the relaxed stability concept would show the biggest performance benefits. The evaluation was based primarily on pilot ratings using the Cooper-Harper rating scale. An example of the results is shown in figure 28. The major conclusion drawn from the study was that it is entirely feasible to utilize low-authority stability augmentation systems as a means of significantly improving operating economics of transport aircraft.

Boeing 747 Ride Quality Improvement and Wing Load Alleviation

Two active control systems to suppress gust induced lateral accelerations were tested on the 747 transport (ref. 70). One was a so-called "Beta-vane" system designed to reduce acceleration levels at the "dutch roll" frequency (approximately 0.2 Hz). The other, called the Modal Suppression Augmentation System (MSAS) was designed to reduce accelerations due to flexible body motions (1.0-3.0 Hz) caused by turbulence. The MSAS system is a single channel augmentation system working via the lower yaw damper servo. The MSAS input signal is derived from the difference between a yaw rate signal from an aft-fuselage mounted gyro (sensitive to dutch roll and flexible mode frequencies) and a yaw rate signal from a c.g. mounted gyro (sensitive only to dutch roll frequencies. The remaining signal then contains only flexible mode frequencies). Flight test results showed the MSAS reduced aft body flexible mode accelerations by approximately 50-percent.

The "Beta-vane" system used for gust alleviation in the frequency range 0-1 Hz is shown in figure 29. The basic sensor is a relative wind vane which is used to sense lateral gusts. The output of the vane is used to drive the 747 upper rudder in a sense that reduces the airplane tendency to turn into the gust. Several flights to investigate performance during turbulence encounters were made. Data from the flight tests indicated that a 50-70 percent reduction in aft body lateral acceleration levels can be achieved.

An active control concept based on use of the outboard ailerons as a load alleviation device used in conjunction with extended wing tips for increased aerodynamic efficiency without structural penalty was also designed for the 747 (ref. 71, 72) and flight tested. The wing maneuver load control (MLC) and gust alleviation (GA) components are shown in figure 30. The c.g. accelerometer, c.g. pitch-rate gyro, and accelerometers on the wing (all triple redundant) sensed motion. Both the MLC and GA subsystems used the outboard ailerons as the control surfaces. The aileron operation for wing-load alleviation generally was symmetrical. Airload redistribution resulted in a pitching moment which required coordinated elevator trim. The MLC function was achieved (as it was for the C-5A and the L-1011) through redistribution of wing spanwise lift to relieve the airload near the tip regions. It was an active-flight-control function rather than gust alleviation, which was an active structural-control function. The GA subsystem suppressed first wing bending motions caused by turbulence. To prevent drag penalties in normal flight the GA subsystem was activated only during severe gust encounters. Analysis of the results of the flight tests indicated fuel savings for the 747 of approximately 1/2-percent which was considered to be sufficiently attractive to consider the application during normal improvement growth of the airplane.

AFTI/F-111 Mission Adaptive Wing (MAW) Technology Demonstrator

The AFTI/F-111 MAW flight demonstrator (ref. 73), designed to demonstrate the feasibility and effectiveness of the concept of using a smooth variable-camber airfoil to reduce the drag at any lift coefficient, makes use of the flight control system composed of two digital systems and two analog backup systems to provide several active control functions. The maneuver camber control mode automatically sets the wing camber to obtain maximum lift/drag using table lookup. The cruise camber control mode maximizes vehicle velocity during straight and level flight at constant power setting by perturbing the flaps. The Maneuver Load Control mode compares computed wing root bending moments against MLC threshold bending moments and operates the outboard flaps to redistribute the wing air load during maneuvers so that the threshold bending moments are not exceeded. The Maneuver Enhancement/Gust Alleviation mode uses optimal control to minimize the response to gusts and to minimize the time to maneuver by appropriate movement of the trailing edge flaps and the horizontal tail. The demonstration program provides the opportunity not only to solve "real-world" problems but also to develop new ideas. It is expected that during the flight test program additional new automatic modes will be developed.

F-18A Active Ride Improvement System

The F-18 is the first production fighter to utilize a digital processor within its flight control computers (ref. 74) which provide primary, secondary, backup, and automatic flight control functional modes. The primary functional modes include a pitch, roll, and yaw command augmentation system, and maneuvering flaps. The automatic flight control functional modes include heading hold, heading select, attitude hold, barometric altitude hold, control stick steering, automatic carrier landing, vector approach, and approach power compensation. An additional active control system was developed to alleviate a limit-cycle type of transonic oscillation (ref. 75) which appeared at low altitude when heavy wing-tip stores were in place, and which produced unacceptable accelerations at the pilot station. The active control system used inputs from the c.g. lateral accelerometer and the roll- and yaw-rate gyros. Based on flight-test data, a gain and phase schedule was developed experimentally and was incrementally fed into the aileron servo. After checkout, the analog system was converted to a digital program and incorporated into the existing flight-control computer.

FIAT G91/T3 Flight Flutter Suppression Study

As a follow-on to the wind tunnel studies of flutter suppression for wings with stores (by means of aerodynamic vanes attached to the store) discussed in the tunnel studies portion of this paper, a flight test program was undertaken using the FIAT G91/T3 as a test bed (ref. 76). The objectives of the study were to obtain first flight experience with a Flutter Suppression System for external stores and to demonstrate a new method for flight flutter testing wing mounted external stores by use of the FSS Automatic Mode Excitation System (AMES). Since the G91/T3 is flutter-free within its flight envelope when carrying its external store inventory, 520-liter fuel tanks were modified to carry the FSS and were ballasted so that flutter could be encountered within the flight operating envelope. Figure 31 shows the test configuration. The store mounted vanes were used to produce aerodynamic forces to counteract the store motion in order to suppress flutter. Special safety features were incorporated and, of course, the tanks could be jettisoned quickly if needed. The FSS/AMES in each tank operated independently of each other. During the flight test it was found that the structural damping of the aircraft was higher than expected. This increased the actual flutter speed to a value that could not be reached. To overcome this problem an artificial flutter case was produced. It was found that the aircraft could be driven into flutter at lower speeds using only one system. The other system was then used to stabilize the flutter. Thus the real increase in flutter speed gained by the FSS could not be demonstrated in flight. However, the increased damping available with the FSS was demonstrated. Figure 32 is an example of the results.

F-4F Flutter Suppression Study

In another flight demonstration of suppression of wing/store flutter, using an F-4F as a test bed, the aircrafts existing ailerons were used (ref. 77). Accelerometers located on the wing provided the signals which were fed back through the existing stability augmentation system (roll channel) of the airplane. Figure 33 shows the locations of the sensors and active controls. Modified actuators were used that had better high frequency characteristics than the standard F-4 actuators. A safety concept (flutter stopper) was incorporated which increases the flutter speed in the event of a system failure by mechanically moving masses in the external store. The main objective of the flight tests, to demonstrate the active flutter suppression system on a divergent flutter mode (exponentially, albeit slowly, increasing amplitudes), was not attained during these flights with high dynamic pressures. The non-linearities in the wing-pylon-external store combination caused a limited amplitude flutter (damping = zero). However, it was demonstrated that a significant increase in the flutter speed was provided by active flutter suppression.

The flutter suppression control law was optimized by means of a linear mathematical model, which was corrected based on test data. Difficulties in the design of the control law were experienced because of non-linear effects of the actuator, the structural non-linearities of the wing/pylon/store combination,and the transonic aerodynamics. The non-linearities also caused considerable problems in the ground and flight tests.

Due to the high degree of amplitude-dependence of the vibration characteristics, the flight tests could only be conducted using small excitation forces. If the amplitude of excitation was too large, the frequency of the flutter critical modes changed, and flutter no longer occurred. For the low excitation, a limited-amplitude flutter occurred.

The active flutter suppression system was successfully demonstrated. At high dynamic pressures, there was some coupling of the flutter suppression system with the aircraft rigid-body mode. The flutter mode was well damped with the active flutter suppression system operating. The aircraft was flown 45 knots above the passive flutter speed, and extrapolated data showed a possible 100-knot increase in speed with the active flutter suppression system operating. This is illustrated in figure 34 (ref. 77).

OH-6A Helicopter Vibration Reduction Flight Tests

As mentioned in the discussion on wind tunnel studies, the concept of using higher harmonic control (HHC) for helicopter vibration reduction has progressed from wind tunnel test to flight test. An OH-6A helicopter has been modified to test the concept in a "real-world" environment. Details of the design of the flightworthy HHC system are given in reference 78. Some of the major components of the system and their functions are indicated in Figure 35 which also shows some results from initial flight tests that have been conducted. Substantial reductions in vibration levels are indicated. The initial tests which were limited to steady state or slowly varying flight conditions pointed the way to an improved system which will be flown in the near future under much more realistic helicopter maneuvering flight conditions.

DAST (Drones for Aerodynamic and Structural Testing) Program

The objective of the NASA DAST program (reference 79) is to pursue investigations in the active controls and aerodynamic loads areas using a series of Aeroelastic Research Wings (ARW) which are flight tested on a modified Firebee II target drone vehicle fuselage utilizing the Remotely Piloted Research Vehicle (RPRV) technique (refs. 80, 81). The first wing to be tested in the DAST program, denoted ARW-1, was a sweptback transport type wing. The primary research objective of the ARW-1 was to develop and evaluate systems synthesis and analysis techniques for the active control of flutter utilizing an onboard Flutter Suppression System. The use of the RPRV technique poses special concerns in the conduct of the flight testing since testing time per flight is quite limited and a higher probability of vehicle loss (both from higher operational risks and the higher technical risks the RPRV method allows) is an accepted risk as opposed to piloted flight testing. In this light, the flight testing of the ARW-1 had the additional objective of developing flutter test techniques for use under these constraints. Reference 80 presents some details of the flutter test technique development and of the implementation of the FSS on the vehicle. A planform drawing of the DAST ARW-1 showing the flutter suppression installation is presented in figure 36. The primary goal of the ARW-1 flight tests was to achieve a 20-percent increase in the unaugmented flutter speed in the Mach number range from 0.8 to 0.9. The operational sequence, as depicted in figure 37, involves an air launch from beneath the wing of a B-52 carrier aircraft; a free flight test phase of between 20 and 40 minutes (depending on Mach number and altitude); and a midair retrieval by helicopter via a parachute recovery system. During the free flight phase, a test pilot controls the vehicle from a ground cockpit. An F-104 aircraft is used as chase and the copilot of this aircraft serves as a backup flight controller for the drone in case of a malfunction with the uplink system. Data from the experiments are provided in real-time to the ground by means of a pulse-code-modulated telemetry system. Experimenters provide real-time assessments of the status of the research wing and its associated active control systems. This assessment is based on the response of the wing to control surface sweeps and pulses. Three flight operations of the ARW-1 were conducted. Very little flutter test data was obtained on the first flight due to operational problems. A good definition of the flutter boundary at Mach 0.92 at 25,000 ft. altitude was obtained on the second flight along with good subcritical damping data. Good FSS-on and FSS-off data was obtained on the third flight. The average rms background acceleration level was approximately 0.25 g, while responses due to FSS excitation signals ranged up to 10 g. Consequently, the signal-to-noise ratio was very high. Figure 38 shows time histories of aileron position and wing-tip acceleration during FSS-off and -on, symmetric, low amplitude frequency sweeps for flight 3 at M = 0.74 and 15,000 ft. The resonance of the bending mode is clearly seen in the FSS-off sweep of fig. 38(a), whereas this mode is heavily damped in the FSS-on sweep of fig. 38(b). Later, the vehicle experienced explosive flutter (due to an error in the implementation of the FSS gain) resulting in separation of the right wing and ground impact. The wing subsequently was rebuilt (designated ARW-1R) with some improvements in fabrication, and fitted to another Firebee fuselage. This wing was destroyed before any flutter suppression data was obtained when the drone recovery parachute deployed and was torn loose on separation of the drone from the carrier aircraft.

Fabrication of the next research wing in the DAST program, ARW-2, was almost complete when ARW-1 was destroyed. This design involved what is believed to be the first exercise of an iterative procedure integrating aerodynamics, structures, and controls technologies in a design loop resulting in flight hardware. Evaluation of multiple active controls systems operating simultaneously, the operation of which is necessary to preserve structural integrity for various flight conditions, is the primary objective of the flight tests on this fuel-conservative-type wing.

The ARW-1 and ARW-2 configurations and research goals are compared in figure 39 (ref. 82). Flight test of ARW-2 is "on hold" pending completion of desirable alterations in the operations procedures and the Firebee test-bed. The first flight of ARW-2 probably is at least two years away.

Other Near-Term Expected Applications of Active Controls in Flight Tests or Operations

Recognizing that there may be plans for the testing or application of active controls for modal suppression or relaxed static stability in aircraft that have not yet appeared in the literature or of which the author is unaware, it never-the-less seems appropriate to mention some known future applications that will broaden the data base in this area.

Reference 54 presents a good overview of foreign advanced aircraft development. It seems that whatever the country and whatever the configuration, nearly all new aircraft are being designed with digital fly-by-wire systems that are oriented to flight control functions integrated with engine and armament controls, and that have relaxed static stability capability. Except for the gust and load control system being designed for the Airbus A-300 with extended wing (described in ref. 83) all the applications are for "rigid-body" functions.

Some advanced U.S. configurations that are in various stages of development and which will make extensive use of FBW and active control concepts are the X-29A Forward Swept Wing demonstrator, the RSRA/X-Wing demonstrator, the combined services advanced helicopter, JVX, and the light attack/utility helicopter, LHX.

The X-29A features in addition to the forward swept supercritical wing an all-moveable canard and variable-camber trailing edge flaps. The flight control system is digital FBW, triplex, and has advanced redundancy management of reliability and failure transient control and evaluation. It has an analog reversion backup system. The automatic active control functions include augmented static stability (static longitudinal stability margin can be as high as -40 percent MAC), and variable camber to minimize drag. There are no functions for control of wing divergence or flutter, however the stability augmentation functions are very sensitive to flexible wing and "rigid body" pitch motions, and is being designed with this in mind.

The X-wing concept involves the use of a 4-bladed rotor with chordwise-symmetric airfoils which may be stopped in flight to become a fixed X-wing for high speed forward flight. Lift and control are provided by coanda blowing from the blade leading and trailing edges, the relative amounts being dictated by the blade azimuth position and forward speed. The concept is to be studied in flight tests using a modified NASA research vehicle, the RSRA (Rotor Systems Research Aircraft). The configuration will feature an integrated quadruplex digital flight control system (engine, compressor, valving). The blade deflections and vibratory loads will be limited by a higher harmonic control system and a hub moment feedback system.

The advanced family of light helicopters known as LHX will have a very sophisticated digital avionic system that will provide highly accurate self-contained position information for navigation and targeting with a digital map. It will function to reduce pilot workload and fatigue with integrated cockpit, voice-interactive and automated functions, artificial intelligence and fusion of sensor data, and vibration reduction.

SUMMARY OF FLIGHT STUDIES

Most of the flight active control studies have focused primarily on rigid body control functions with some notable exceptions. Maneuver and gust load alleviation, and relaxed static stability have received considerable attention in flight studies. With the exception of the B-52 CCV flight program, evaluations have been limited to a single control function. Only four active flutter suppression flight studies are known. Three involved manned aircraft (military type) which were modified with external stores to produce a "mild" flutter mode which in an emergency condition could be stabilized by changing inertia properties or dropping the stores. The DAST program is the only study focused on high speed transport configurations. Except for the DAST vehicle, all flight flutter suppression systems were retrofitted. Also, as far as is known by the author, except for the DAST program there are no firm plans for future flight studies of active flutter suppression to assess at higher speeds the integration of flutter suppression with other control functions as was done at low speeds with the B-52, or to assess real-world capabilities of flutter suppression systems to control the (usually) more violent classical wing bending/torsion flutter (vs. wing/store flutter) at high speeds. Most of the current and planned flight studies are focused on flight path and configuration control, relaxed static stability, and maneuver/gust load alleviation.

CONCLUDING REMARKS

Most of the experimental studies and applications of active controls concepts that have been made over the past 20-years have been reviewed. Supplementary experiments that relate to active controls technology such as unsteady pressure measurements on oscillating wings or controls have not been addressed.

Based on this review, several conclusions can be made. In a broad sense, wind tunnel studies have focused primarily on flutter suppression and to a lesser extent, on load reduction whereas flight studies have focused primarily on rigid body control functions with some notable exceptions. Maneuver and gust load alleviation, and relaxed static stability have received considerable attention in flight studies. In both wind tunnel and flight studies, with the exception of the B-52 CCV flight program, evaluations of aeroelastic active control concepts have been limited to a single control function. Comparisons of predicted and experimental results mostly have been for the subsonic speed regime where the use of linear aerodynamics is appropriate. At higher transonic speeds one has to deal with the limitations of nonlinear aerodynamics in control design theory and problems of predicting control surface effectiveness, also a problem at lower speeds. Three of the four flight flutter suppression studies were oriented to military aircraft (B-52 and fighters carrying external stores). The DAST flight tests are the only studies focused on high speed transport configurations. Also, except for the DAST vehicle, all flight flutter suppression systems were retrofitted. A surprising (to the author) amount of experience has been gained in the application of digital fly-by-wire control systems to stability and command augmentation functions and to vehicle configuration control functions. In the civil/transport area relaxed static stability, ride improvement, and load control obviously are seen as high pay off areas for active controls applications. Except for some relaxed static stability applications, past experience has been with non flight-critical functions.

The feasibility of controlling flutter with active controls has been demonstrated convincingly in wind tunnel studies, but there is a need for further evaluation of systems for controlling explosive flutter. Also, the capabilities of adaptive flutter suppression systems need to be explored further. The interactions of multiple aeroelastic control functions operating simultaneously need to be evaluated in flight tests in the difficult transonic speed range as was done in the relatively low speed CCV-B-52 tests.

Finally, although more and more active controls concepts are being introduced into flight systems the greatest potential benefits will accrue only when totally integrated systems including relaxed stability, maneuver and gust load alleviation and flutter suppression are considered as part of an integrated design process starting with preliminary design.

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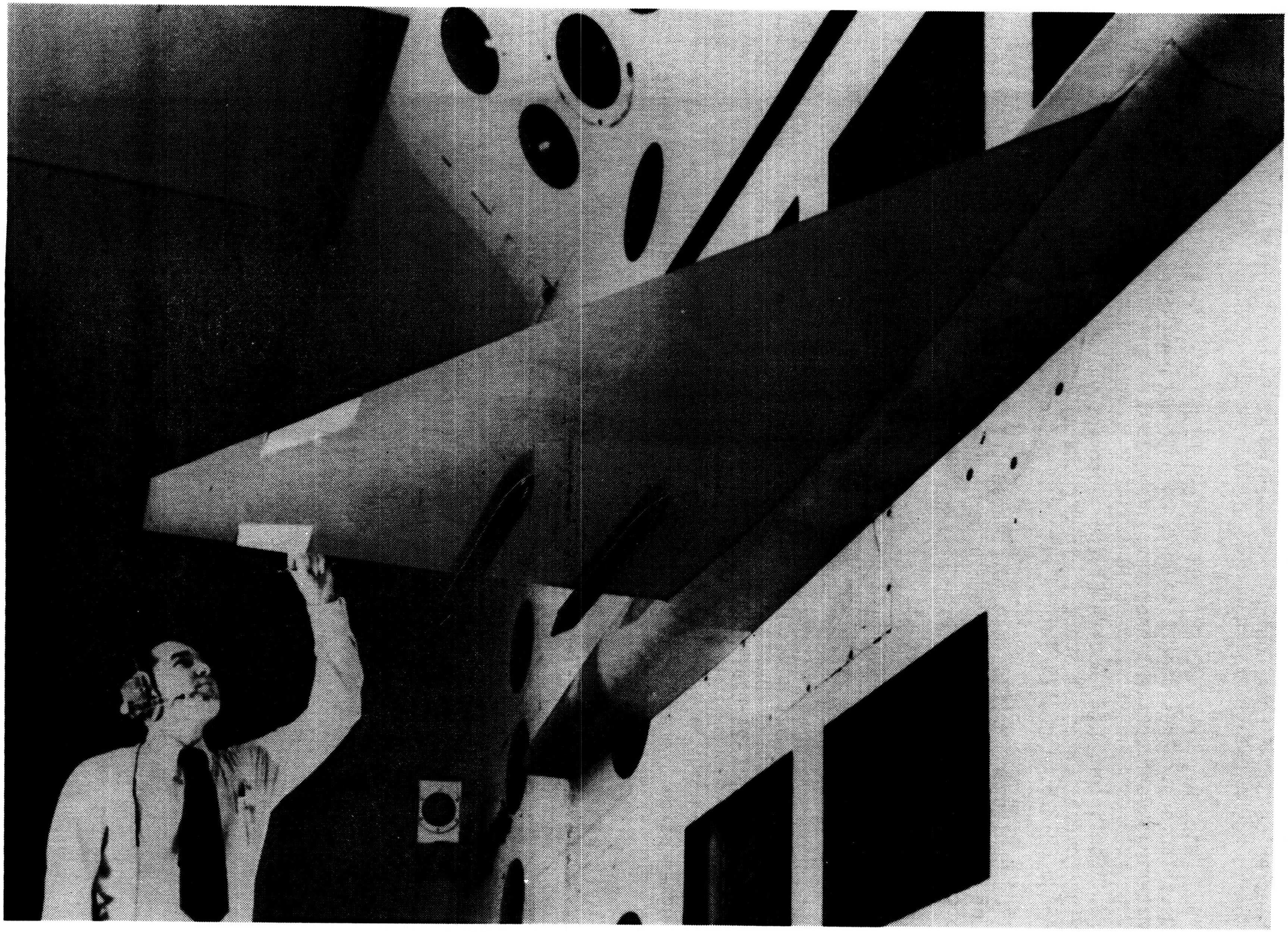


Figure 1.- Delta wing flutter supression model. (Ref. 19)

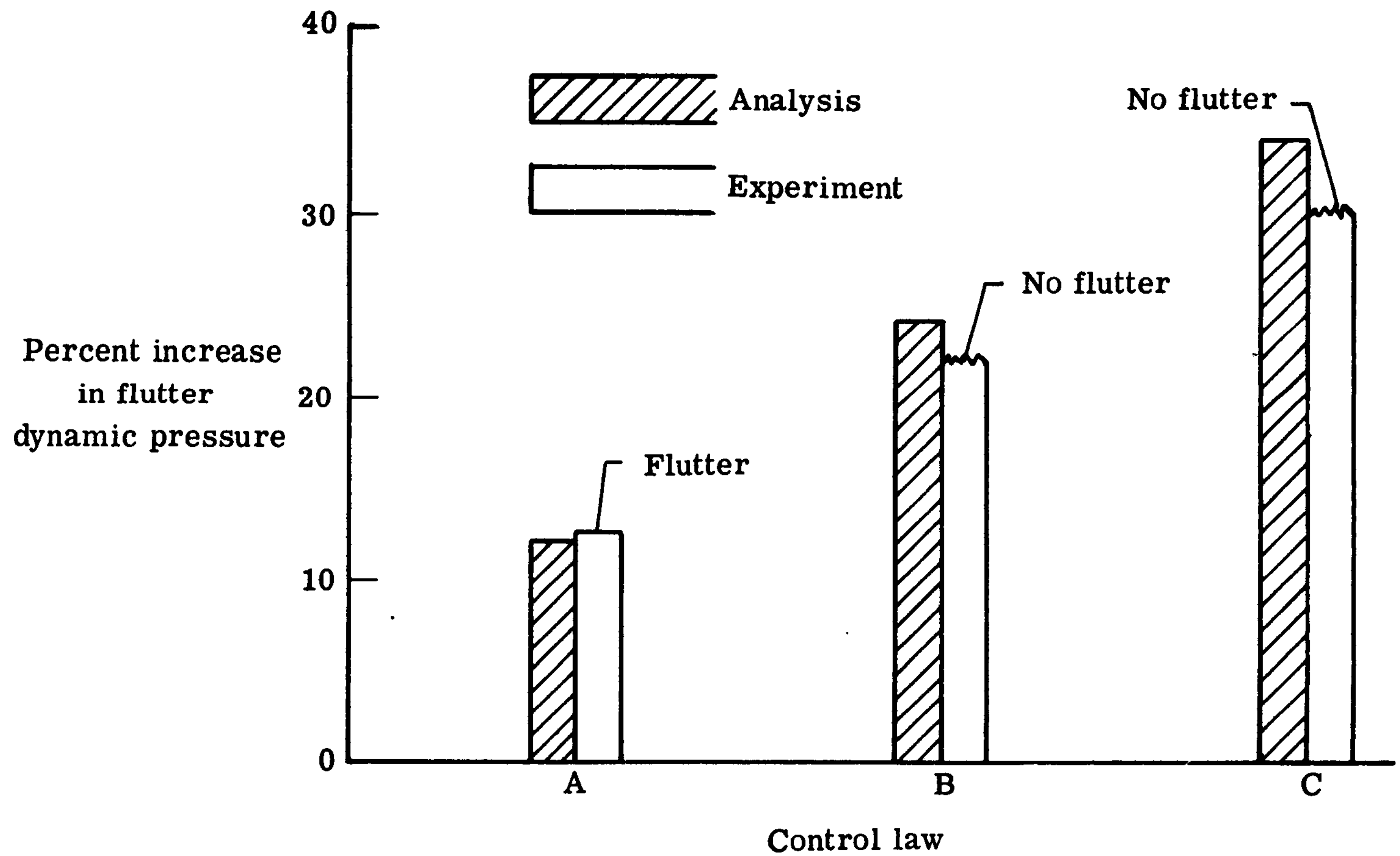


Figure 2.- Effect of different control laws on flutter dynamic pressure at M = 0.9. (Ref. 19)

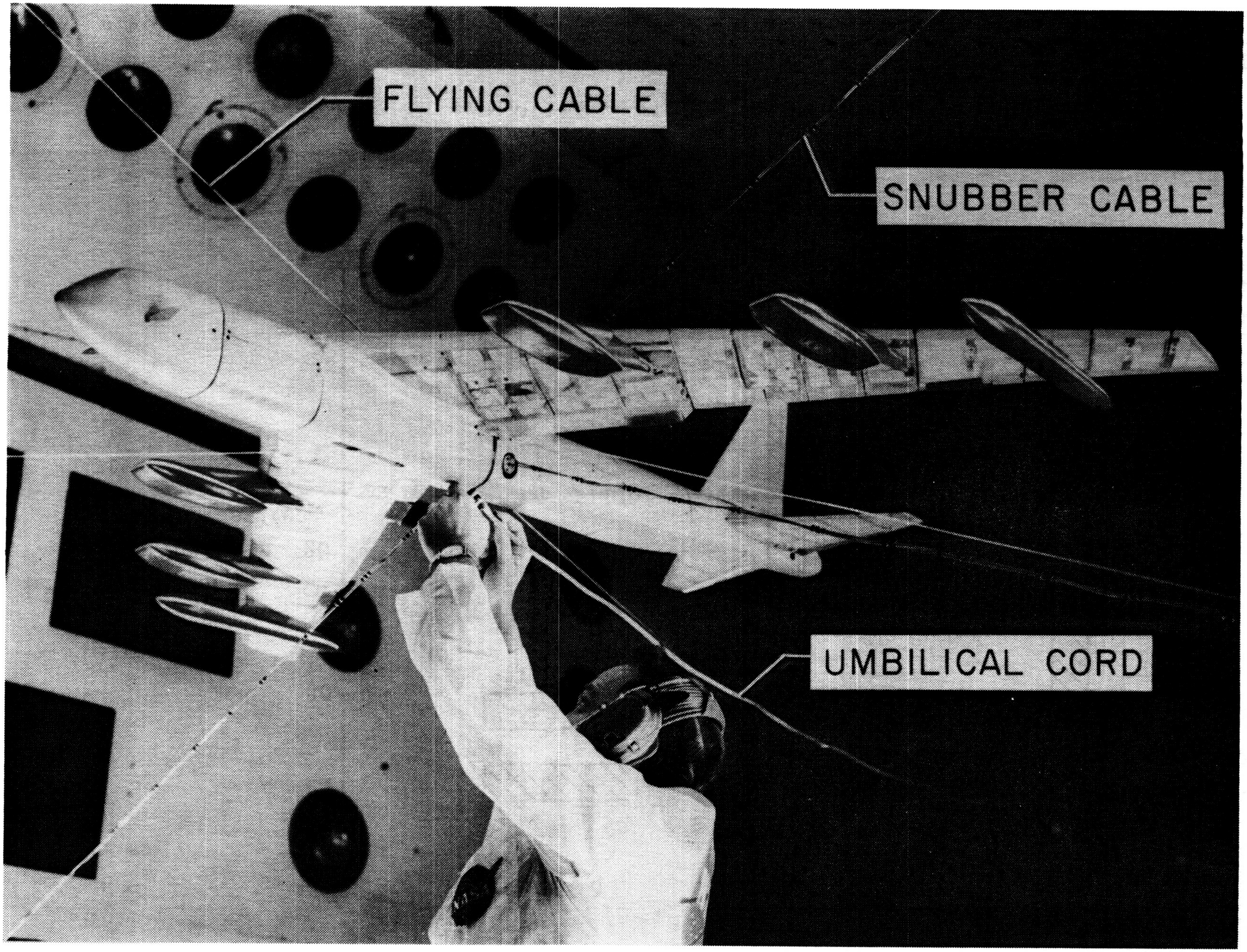
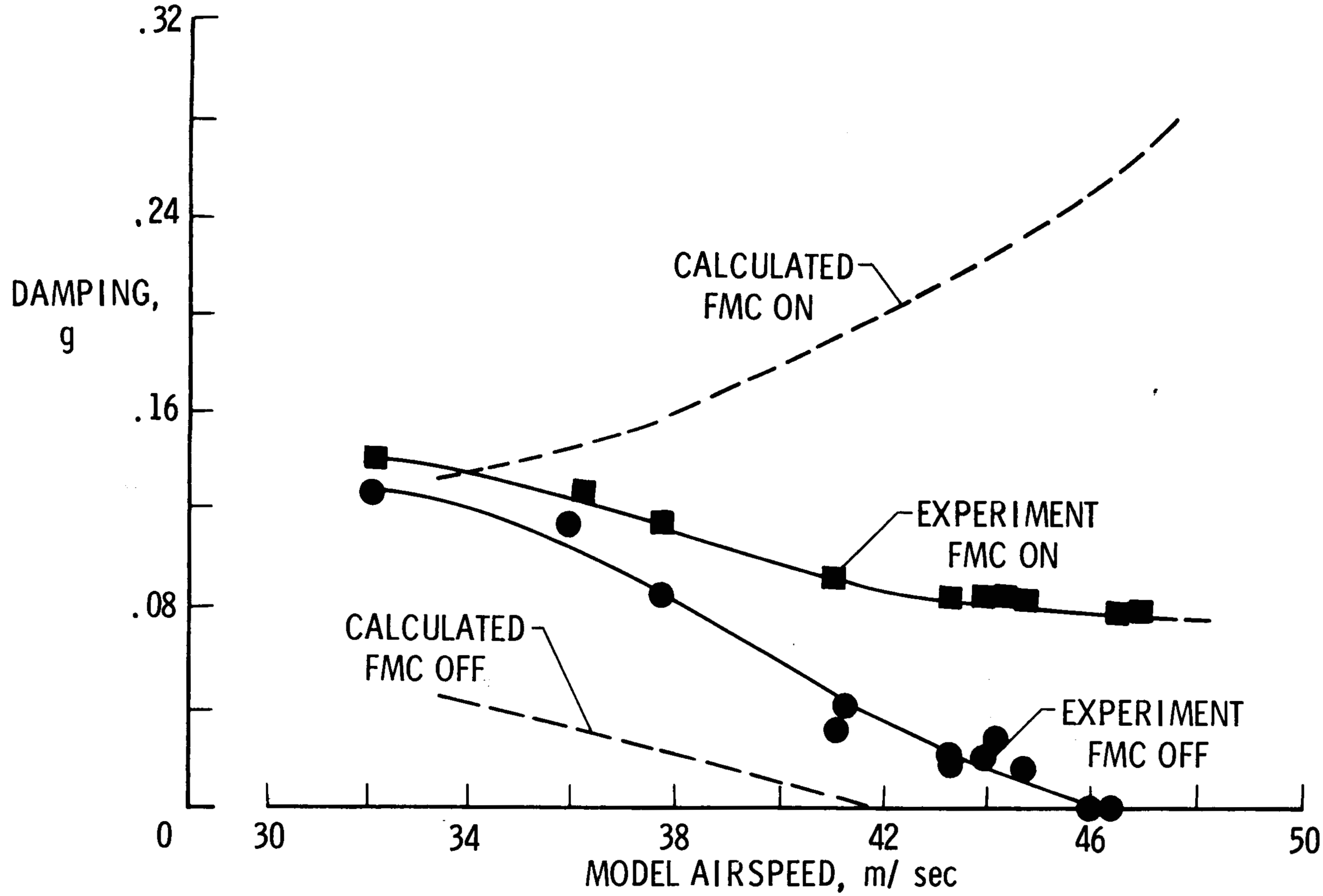
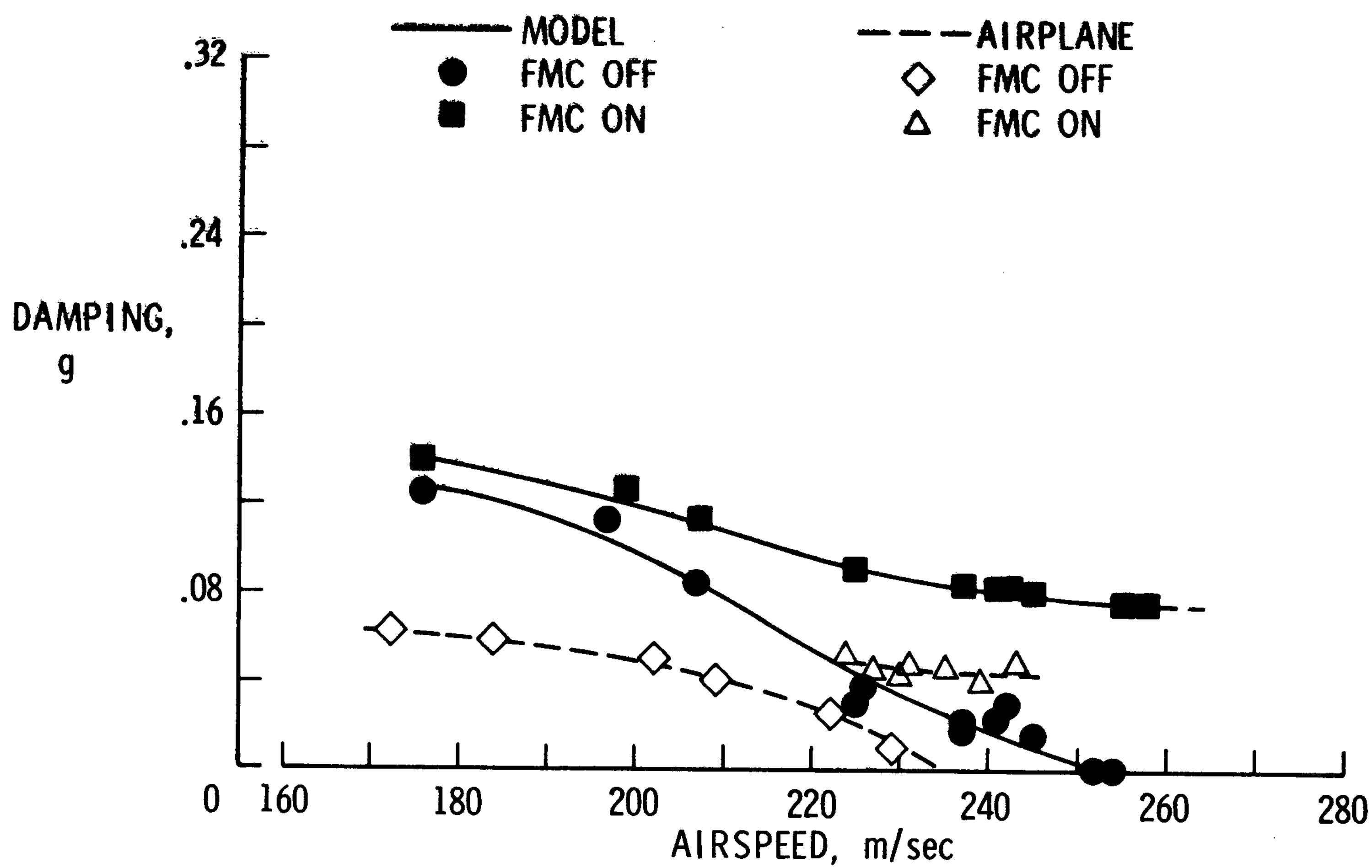


Figure 3.- B-52 CCV model mounted in NASA Langley Research Center Transonic Dynamics Tunnel.



(a) Measured and calculated values

Figure 4.- Comparison of B-52 flutter mode damping characteristics.



(b) Model and airplane values

Figure 4.- Concluded.

FREQUENCY RESPONSE TO CANARD EXCITATION

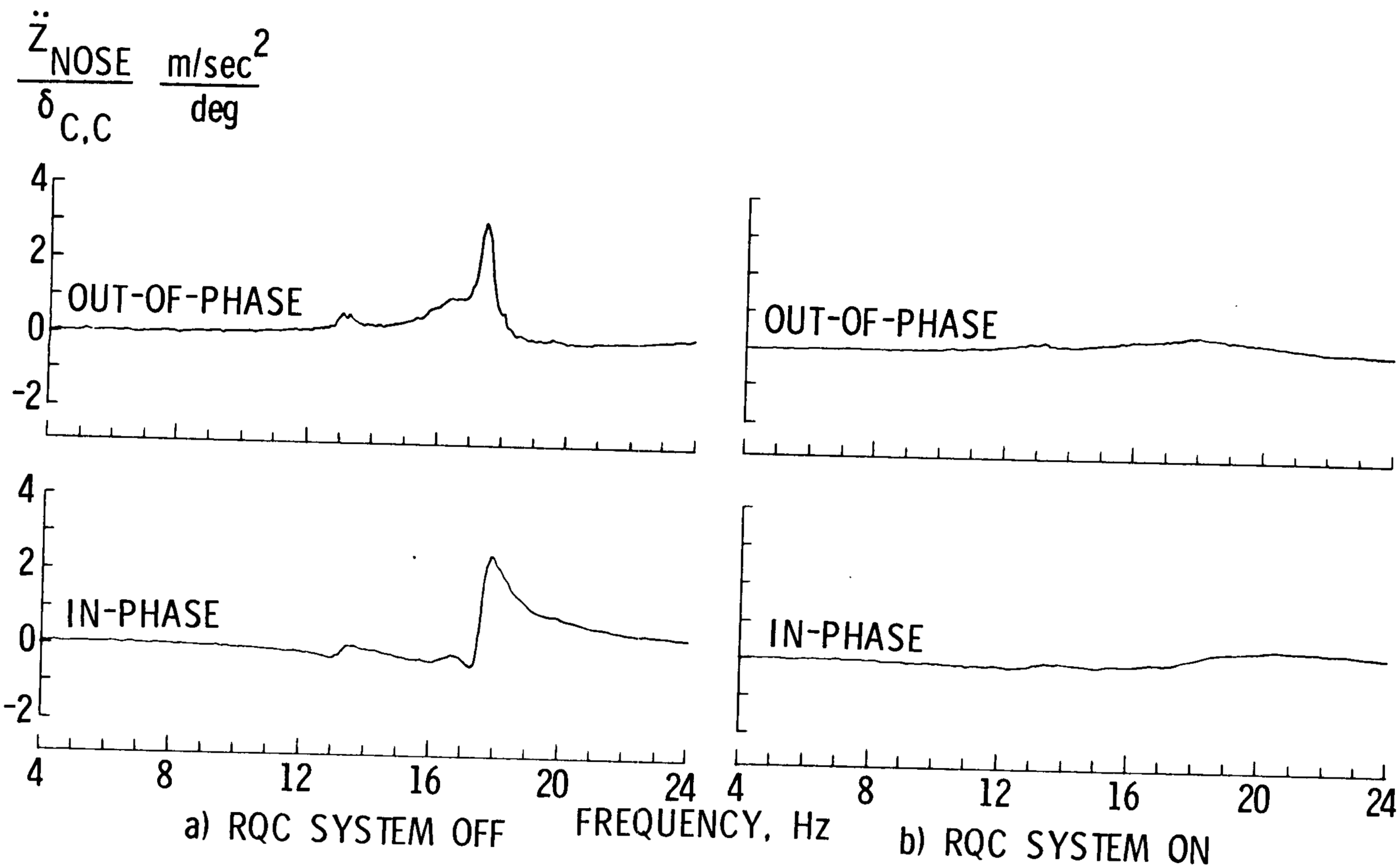
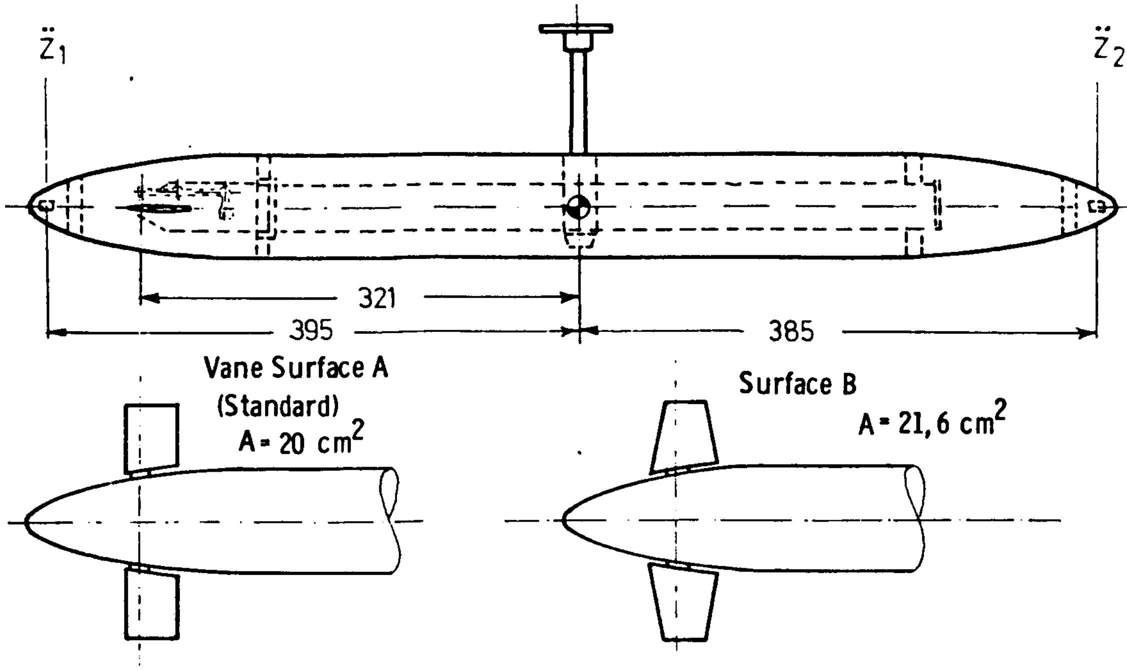


Figure 5.- Measured frequency response of B-52 model to canard excitation at a velocity of 33.7 m/sec. (Ref. 23)



Vane-tank

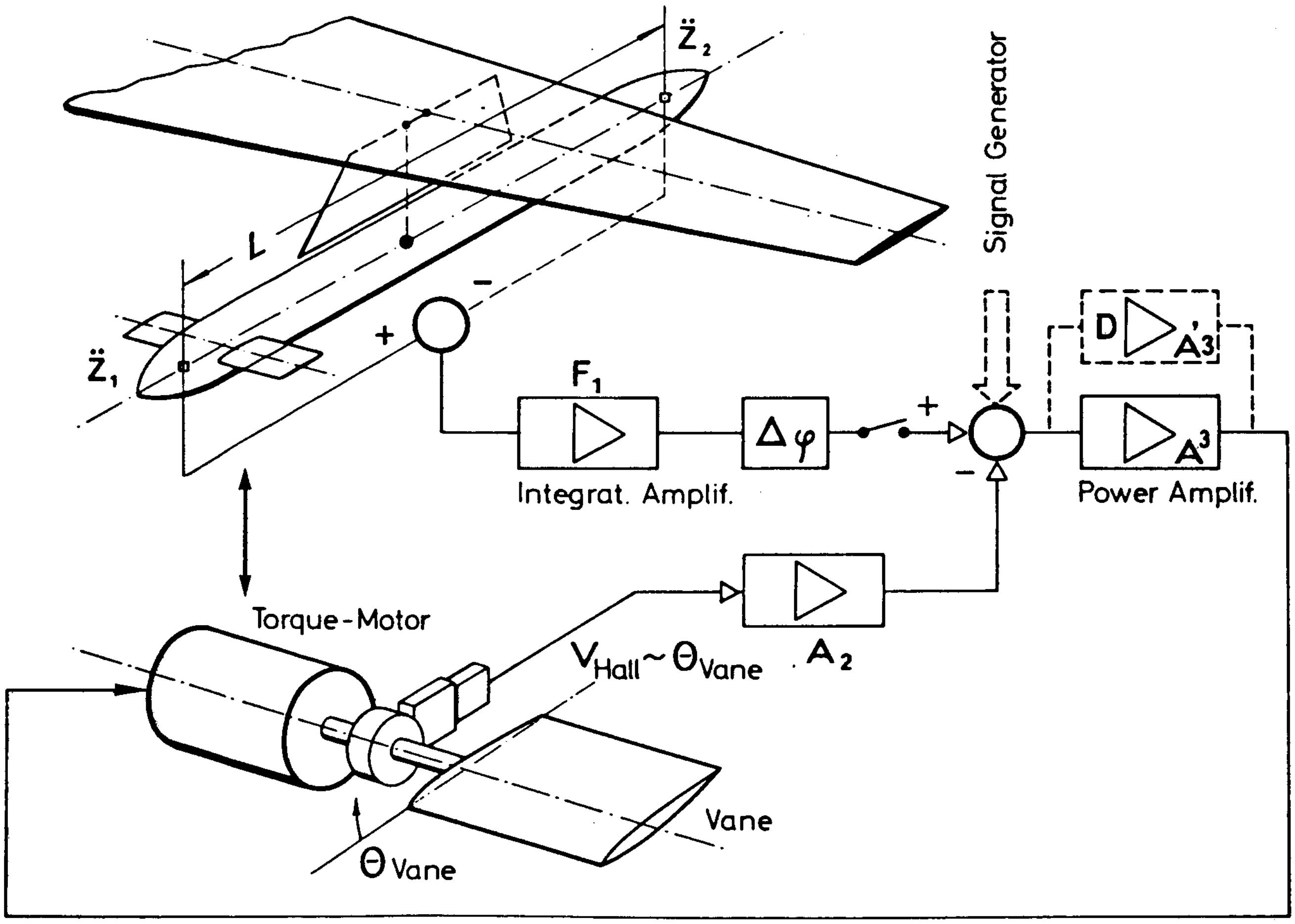


Figure 6.- Block diagram of the vane control system.
for configuration studied in ref. 24.

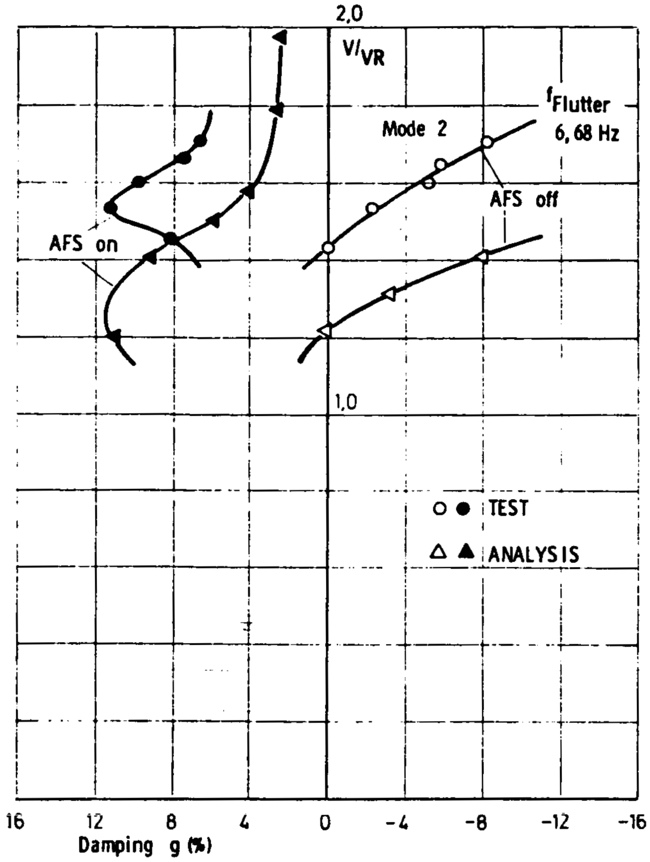
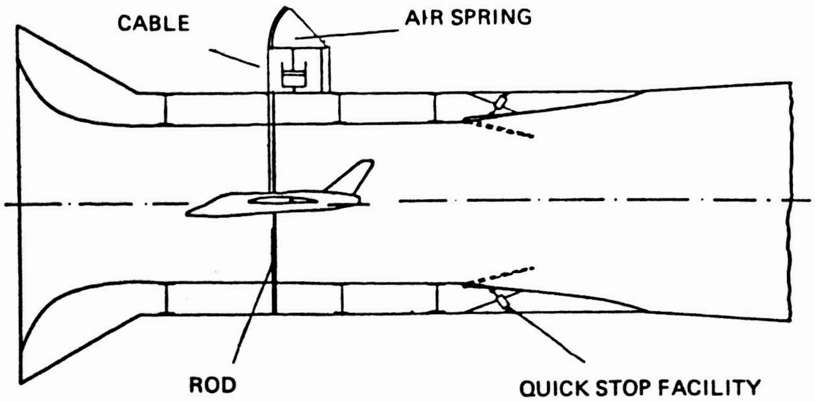


Figure 7.- Comparison of measured and calculated damping versus velocity Λ_{WG} = 45°. (Ref. 24)

A-19



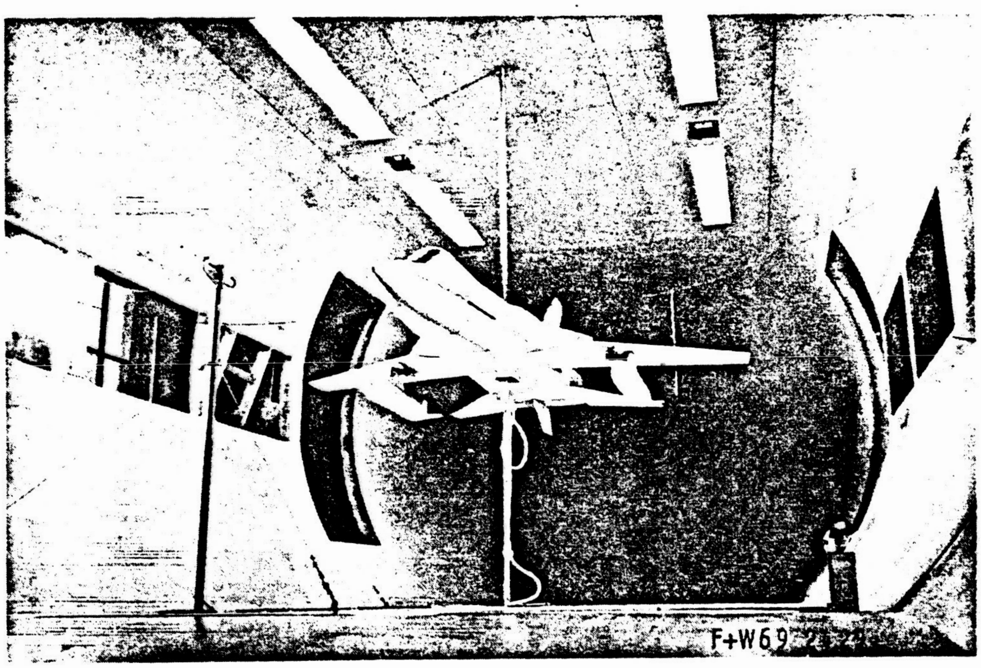


Figure 8.- Flutter tunnel and model suspension. (Ref. 26)

Ref 21

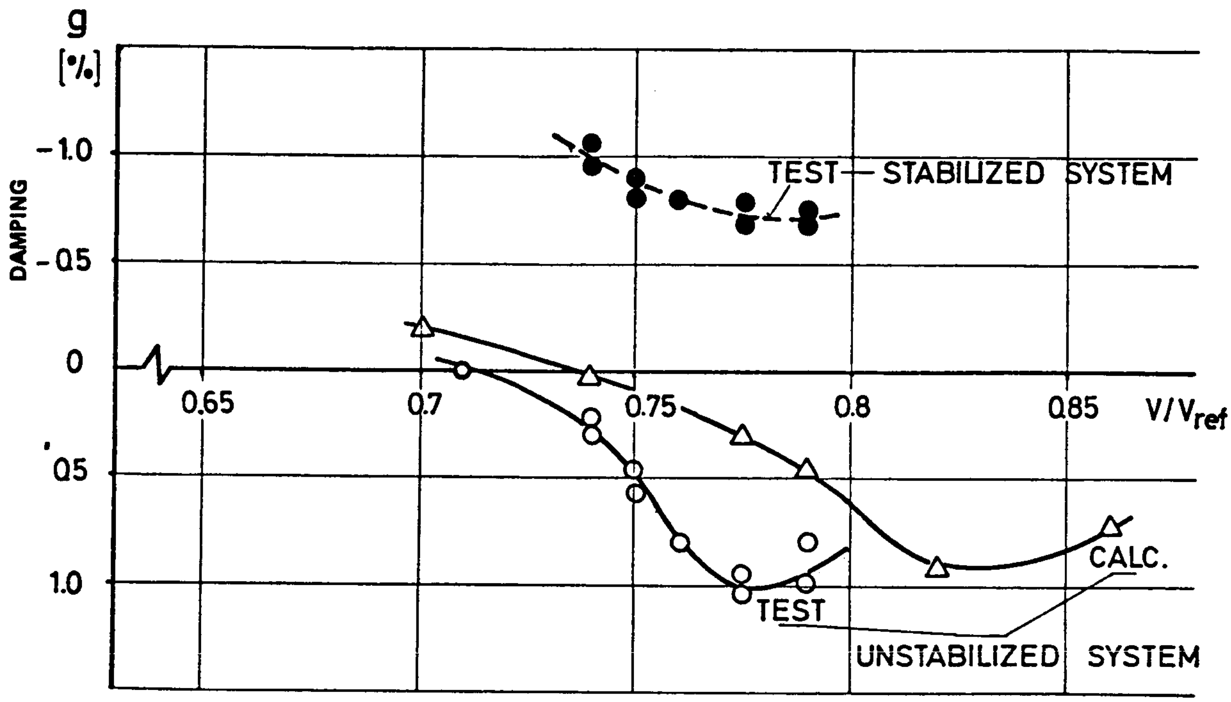


Figure 9.- Flutter speed versus damping for stabilized and unstabilized system. (Ref. 26)

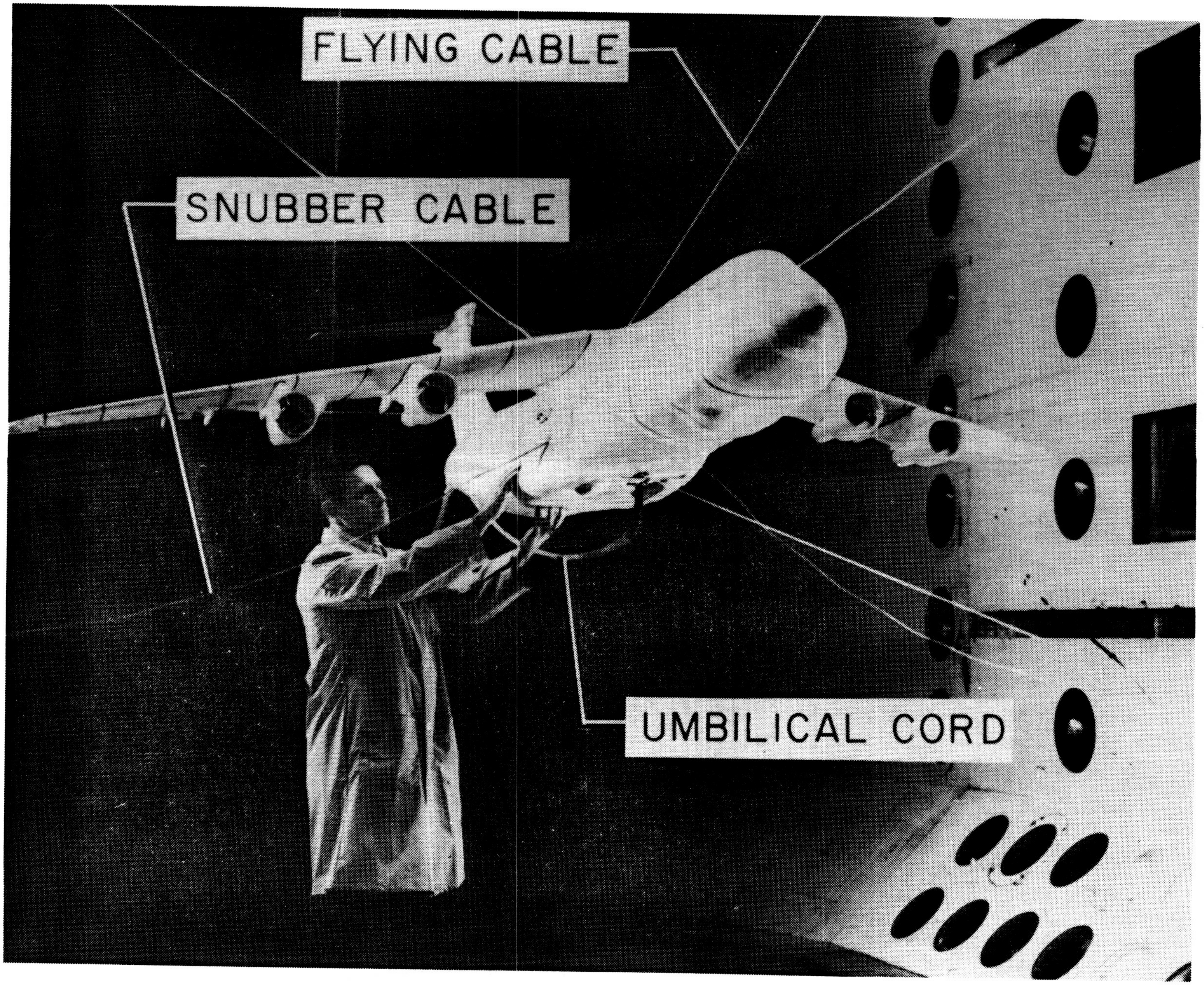


Figure 10.- C-5A model mounted in Transonic Dynamics Tunnel. (Ref. 23)

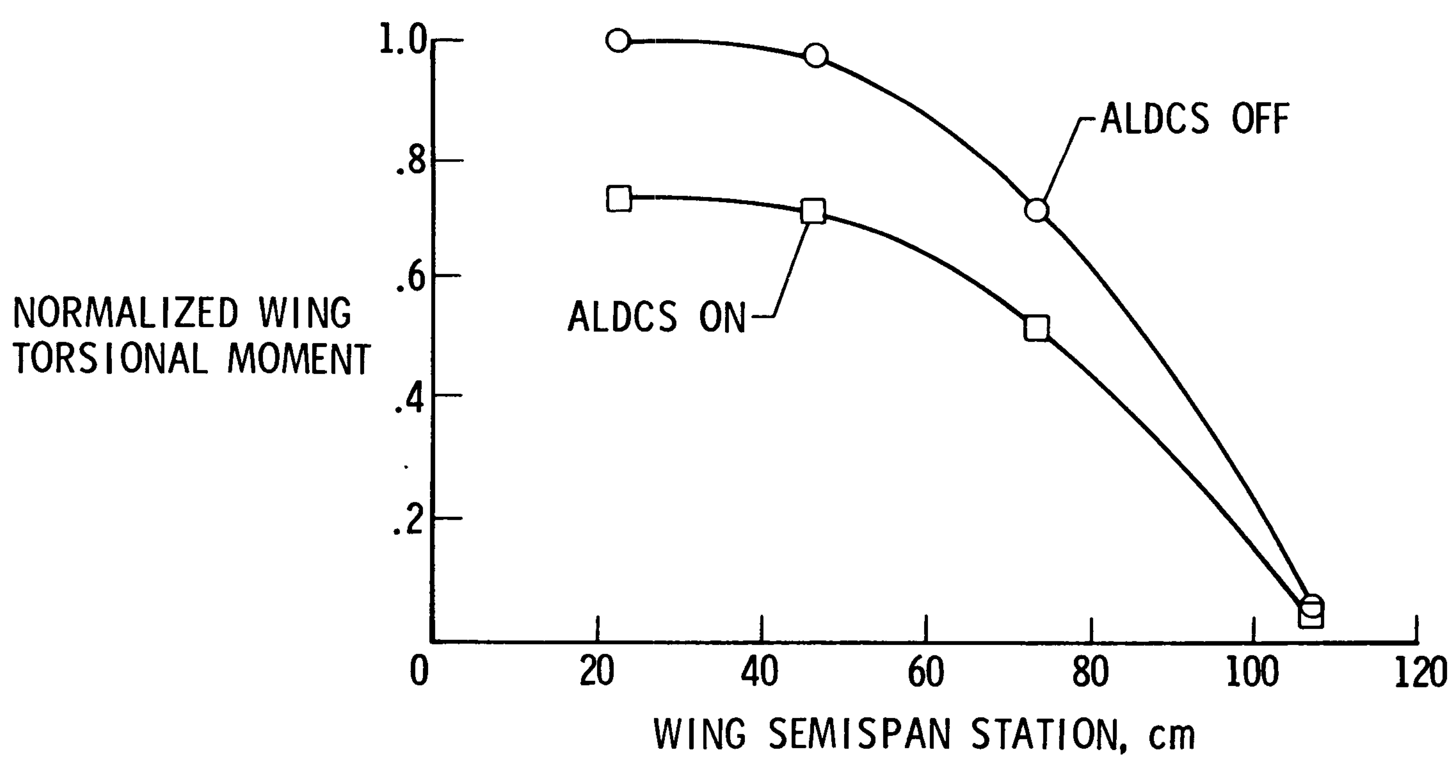


Figure 11.- Spanwise distribution of C-5A model normalized dynamic wing torsional moment at 11 Hz.

(Ref. 23)

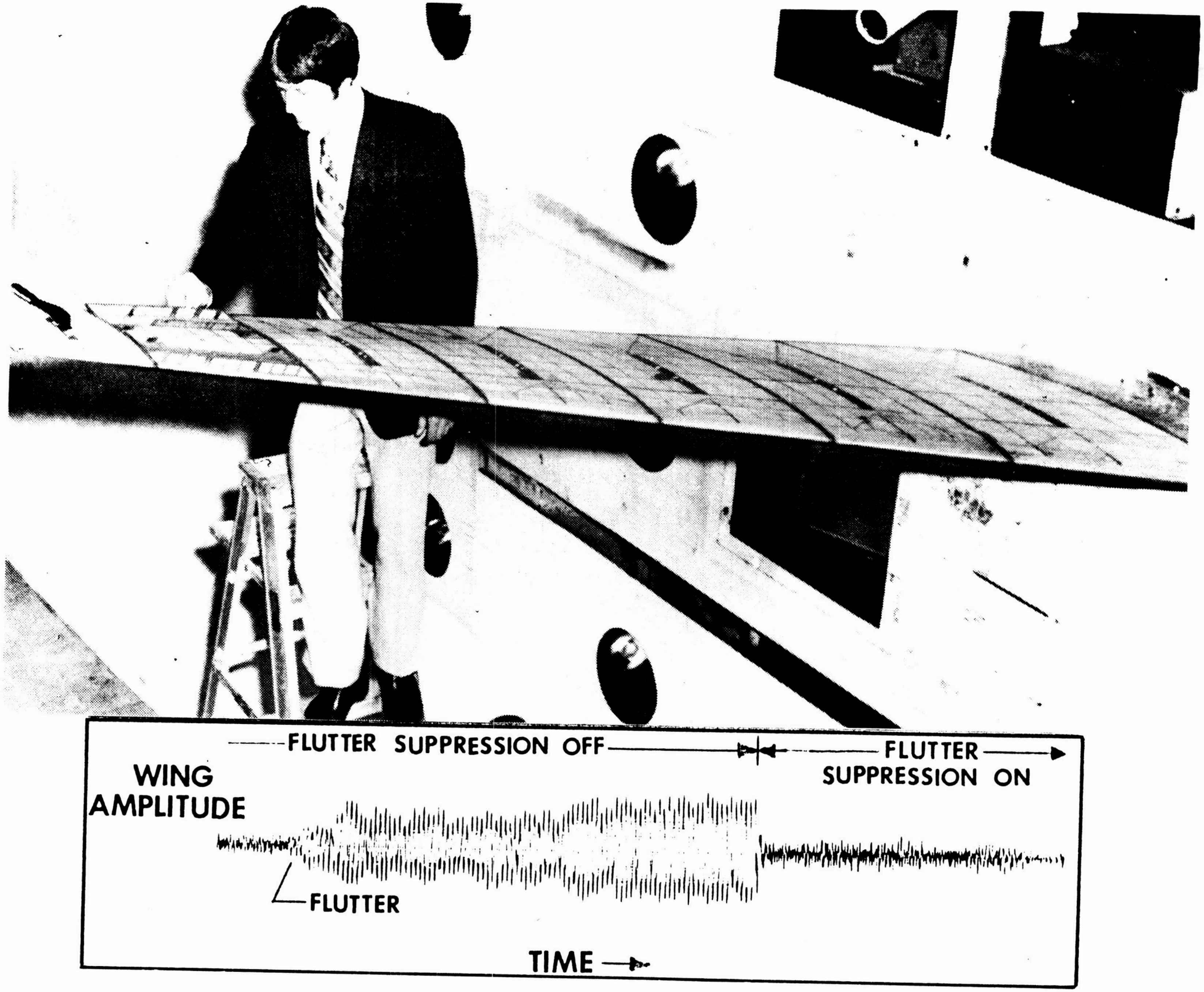
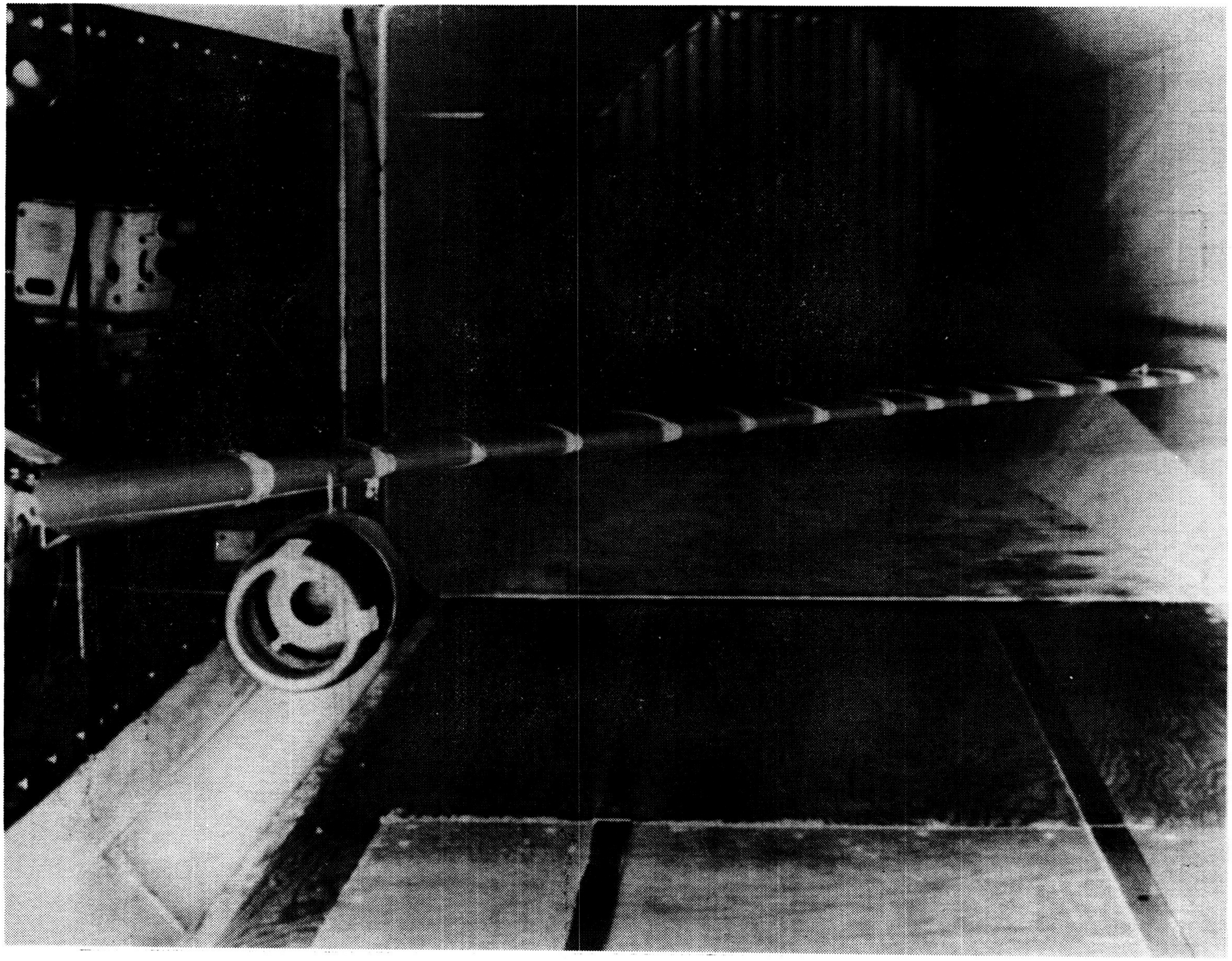
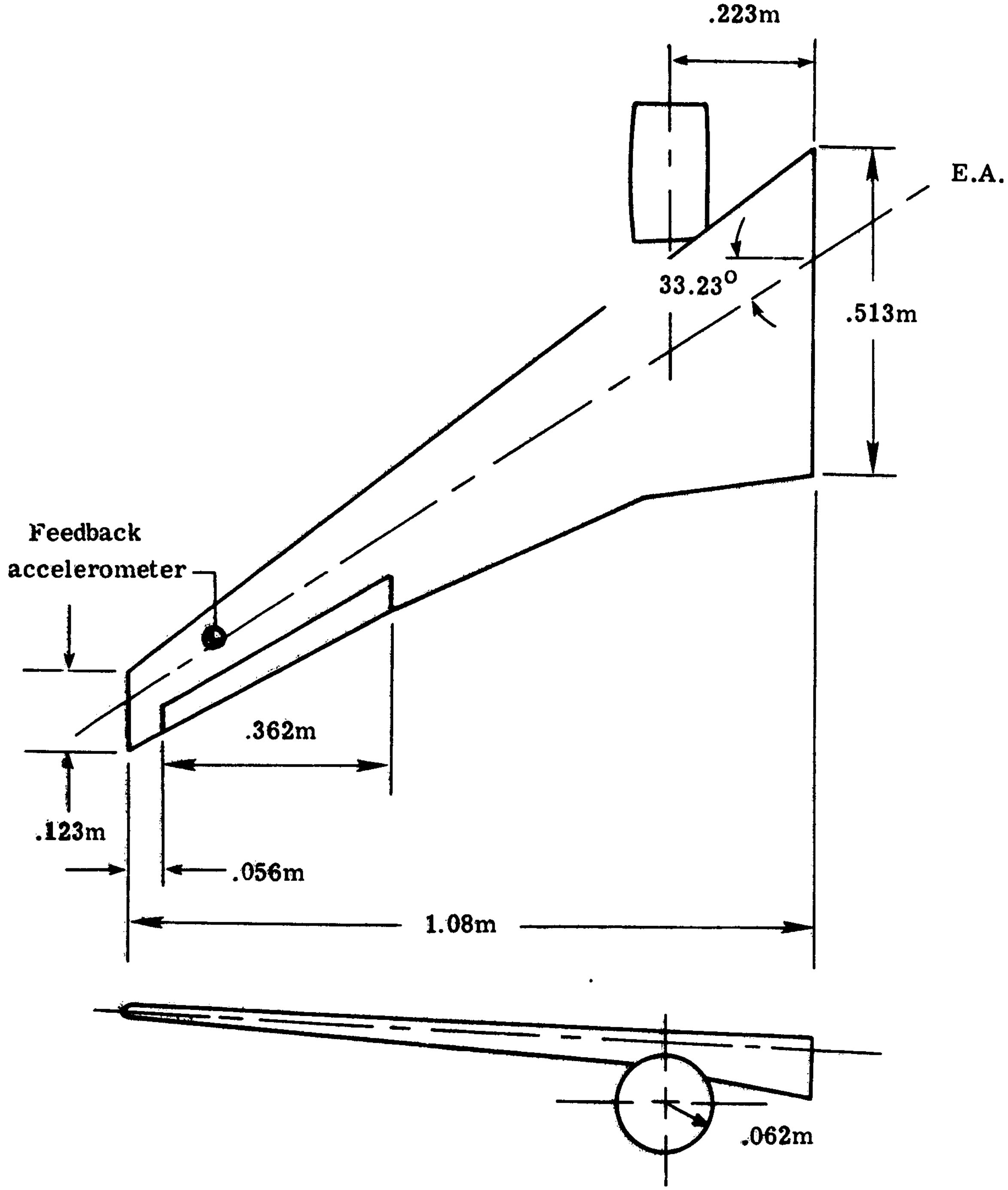


Figure 12.- DAST wing mounted in TDT and sample of FSS results.



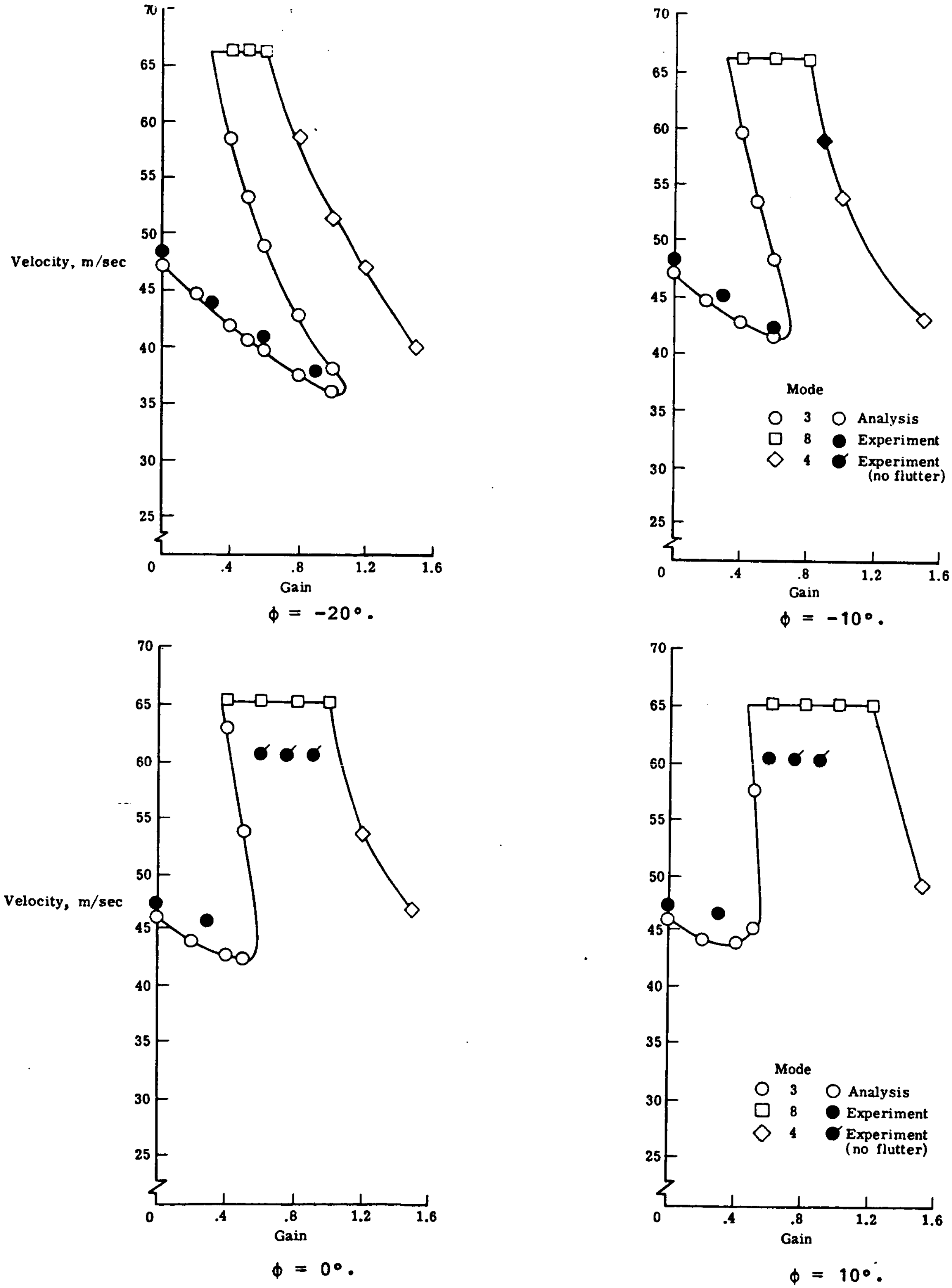
(a) Model in Douglas Aircraft Company low speed tunnel.

Figure 13.- DC-10 derivative model flutter suppression studies. (Ref. 30)



(b) DC-10 derivative model configuration and dimensions.

Figure 13.- Continued



(c) Example of measured and predicted flutter velocities as function of gain and phase for control law 1.

Figure 13.- Concluded.

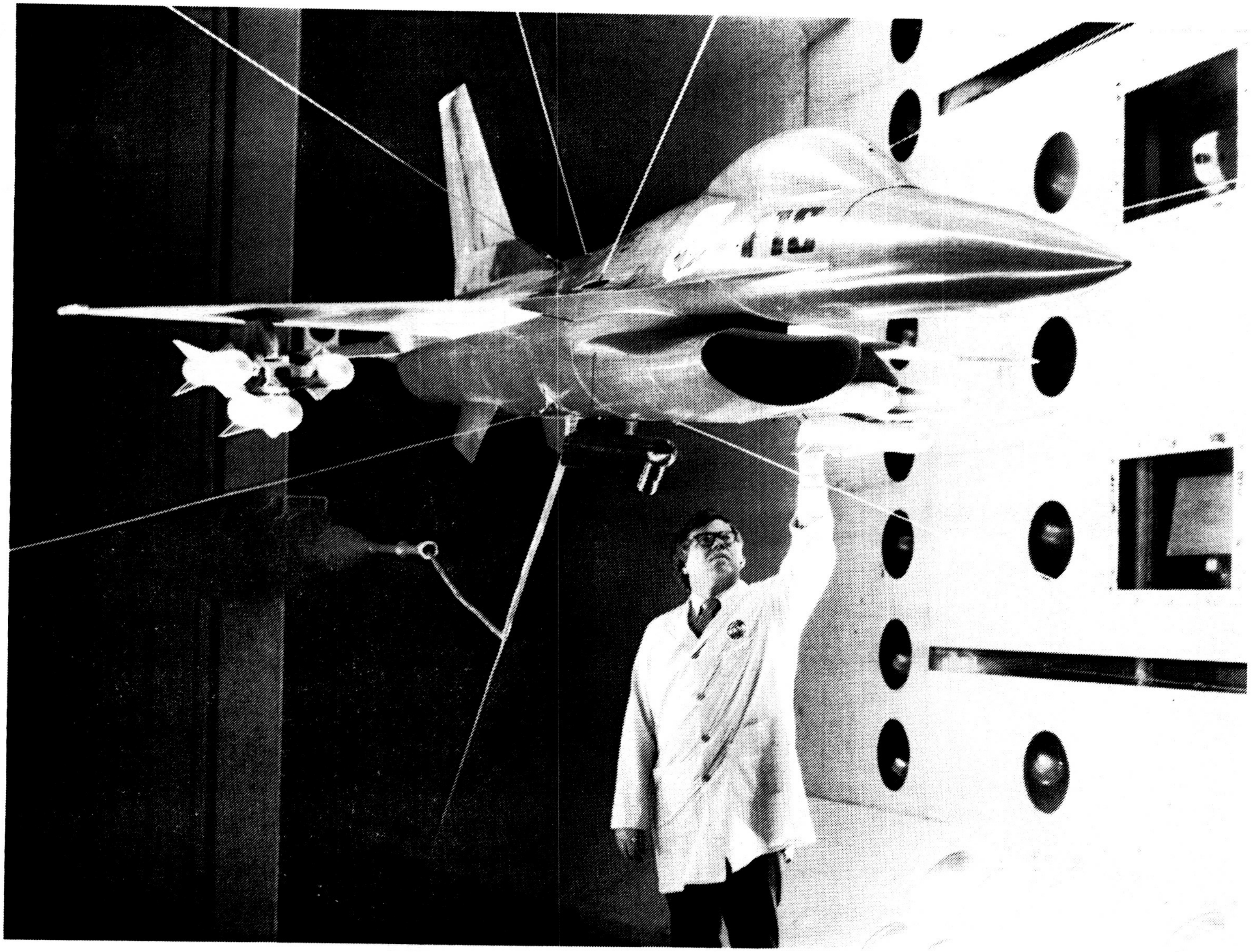


Figure 14.- F-16 model in TDT on cable system.

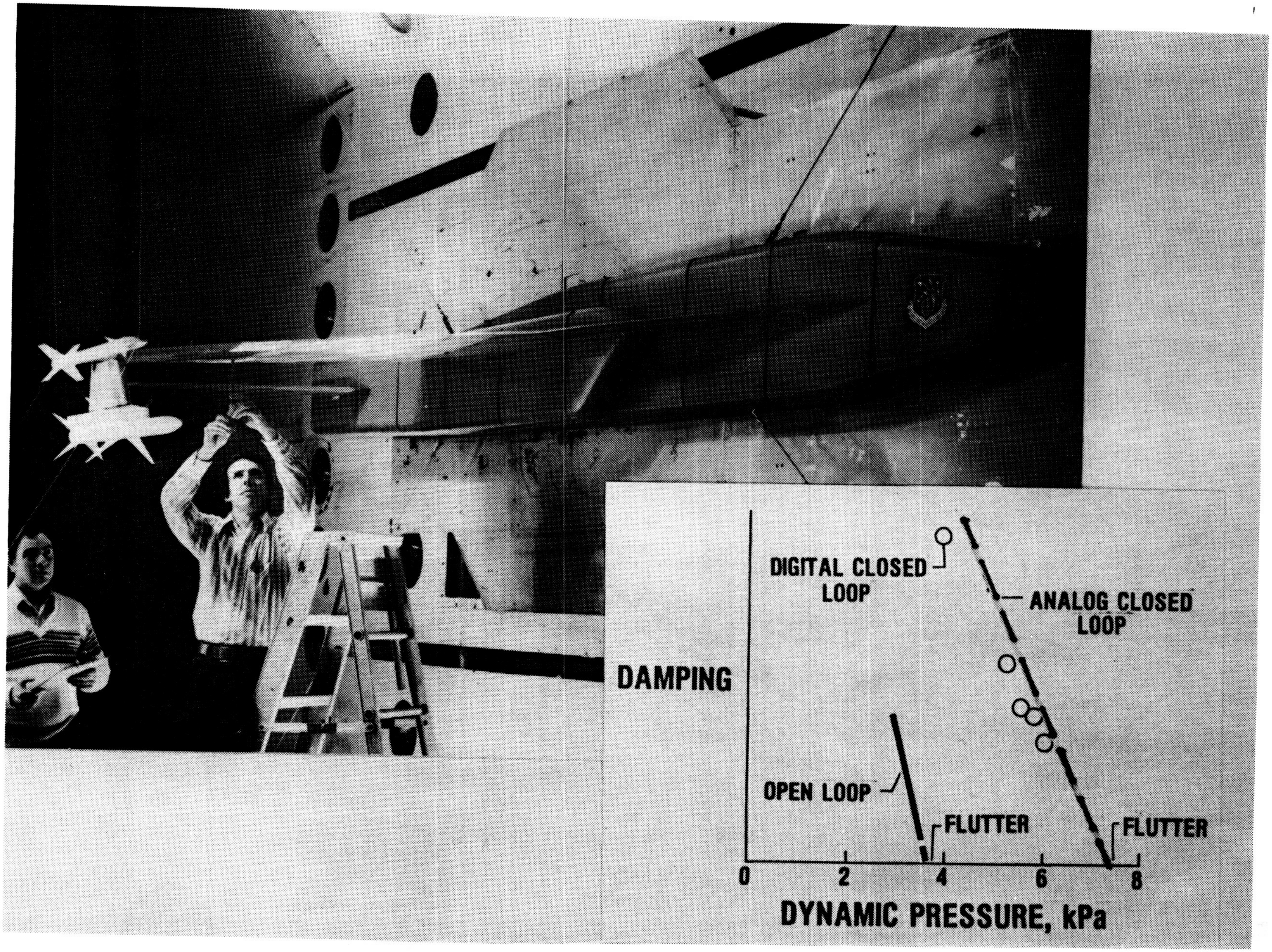


Figure 15.- YF-17 active control model in TDT with sample results.

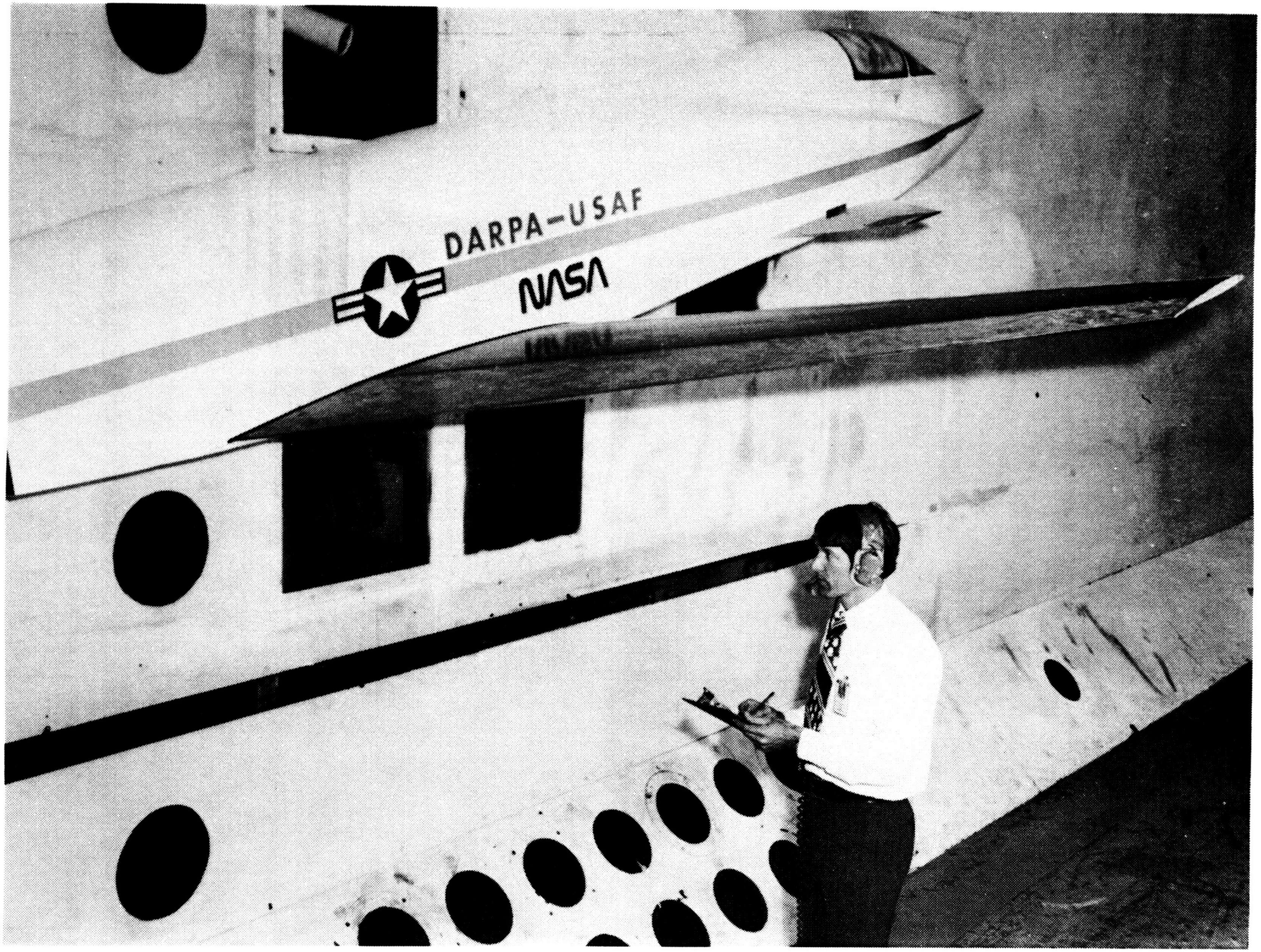


Figure 16.- Forward swept wing flutter model with actively controlled canard in NASA Langley TDT.

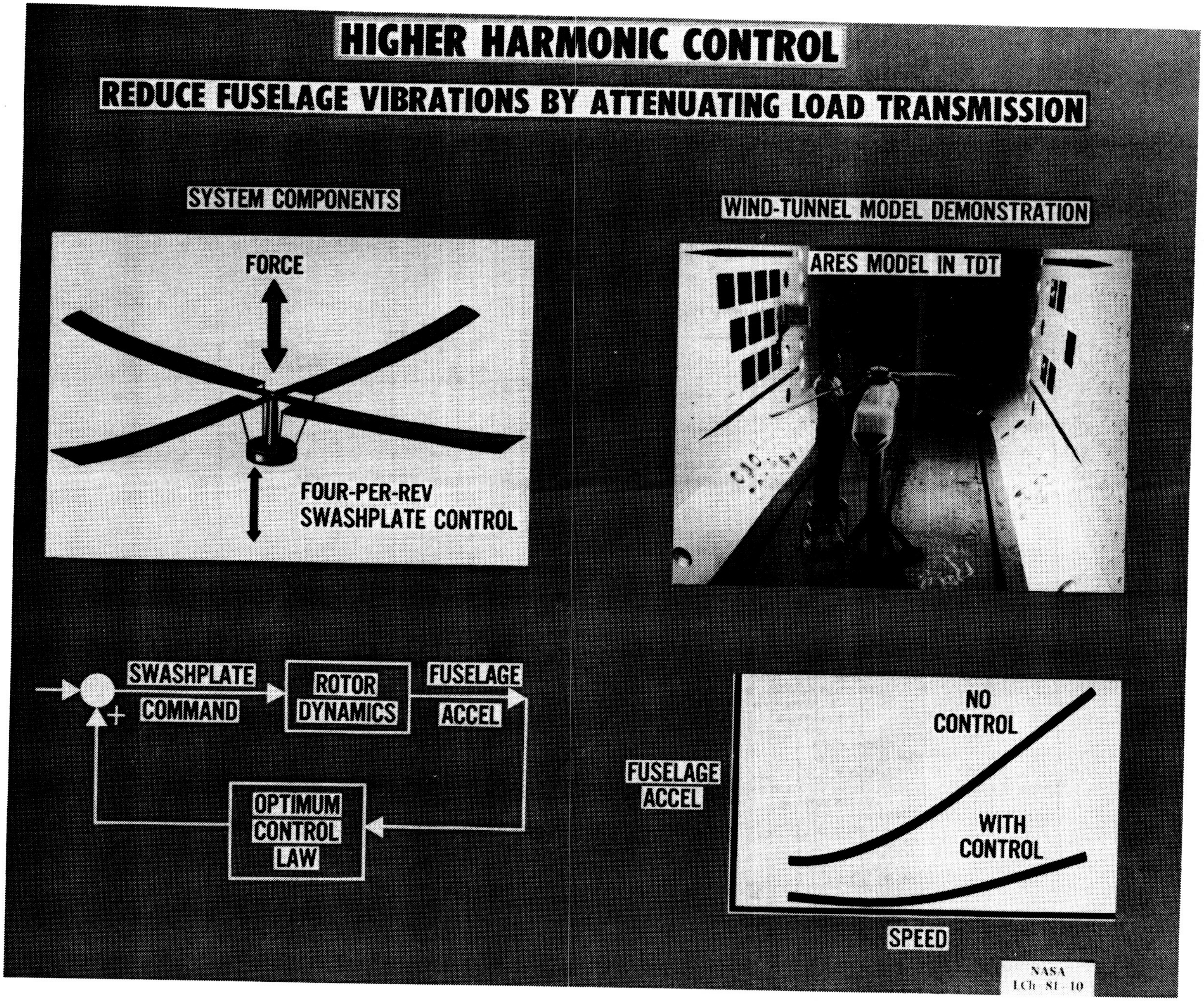


Figure 17.- Higher harmonic control benefits demonstrated in TDT studies.

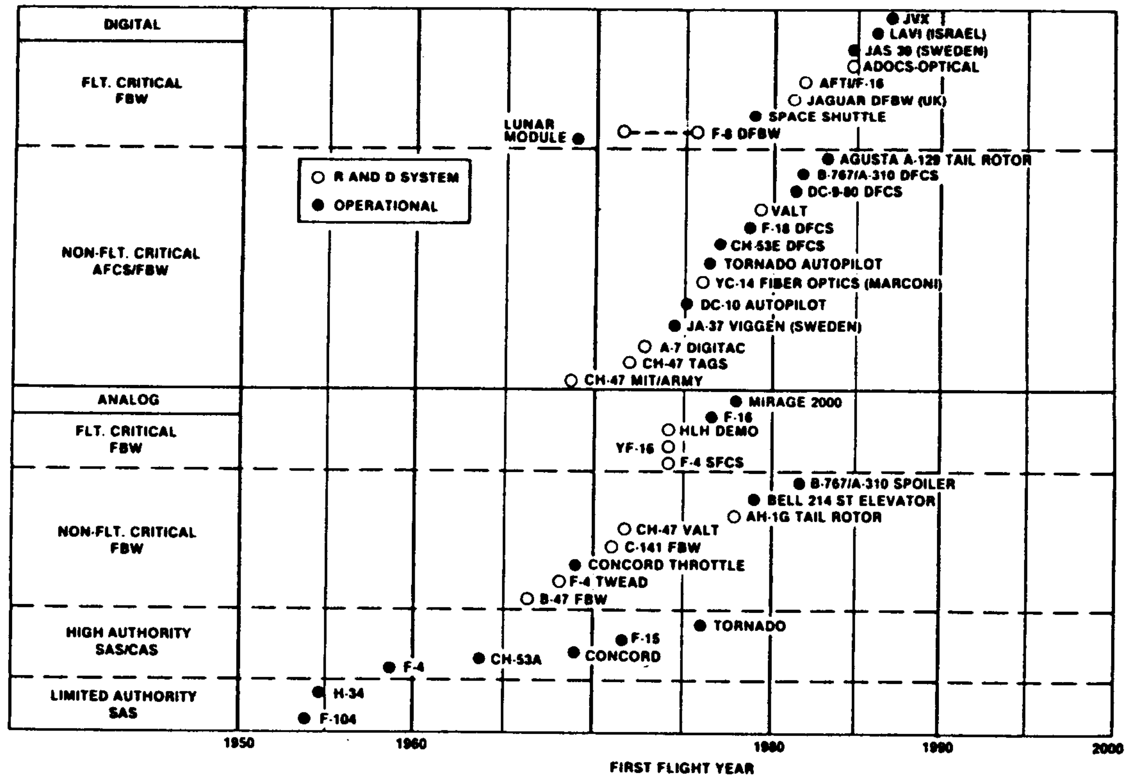
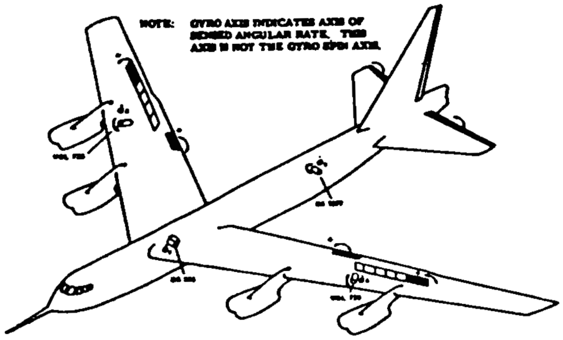


Figure 18.- Evolution of flight controls technology. (Ref. 54)

LAMS LONGITUDINAL AXIS



LAMS LATERAL - DIRECTIONAL

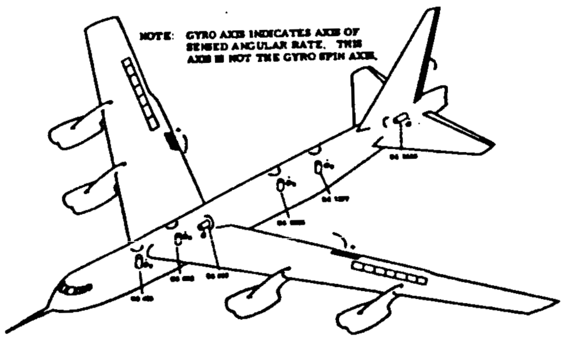


Figure 19.- LAMS control surfaces and gyros. (Ref. 44)

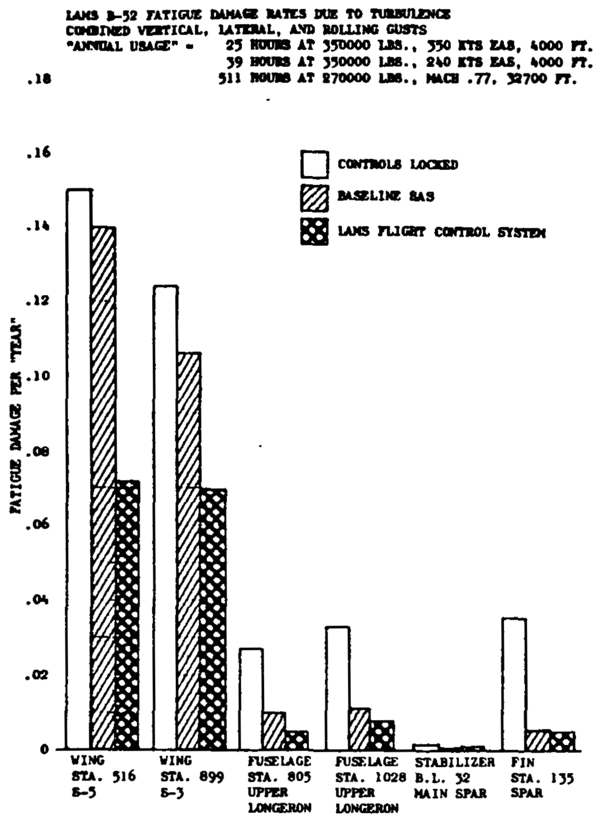
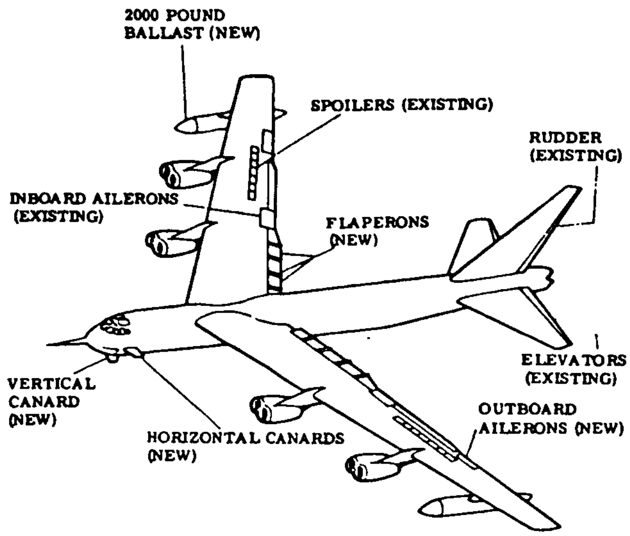


Figure 20.- Fatigue damage rates. (Ref. 44)



	SURFACE	SURFACE REQUIRED PER CONCEPT				
		RC	FMC	MLC	AS	FR
EXISTING	ELEVATOR			X	X	X
	RUDDER				X	
NEW	OUTBD. AILERON		X	X		X
	FLAPERON		OUTBD SEG.	X		
	VERTICAL CANARD	X				
	HORIZONTAL CANARD	X				

Figure 21.- CCV B-52 flight control surfaces. (Ref. 44)

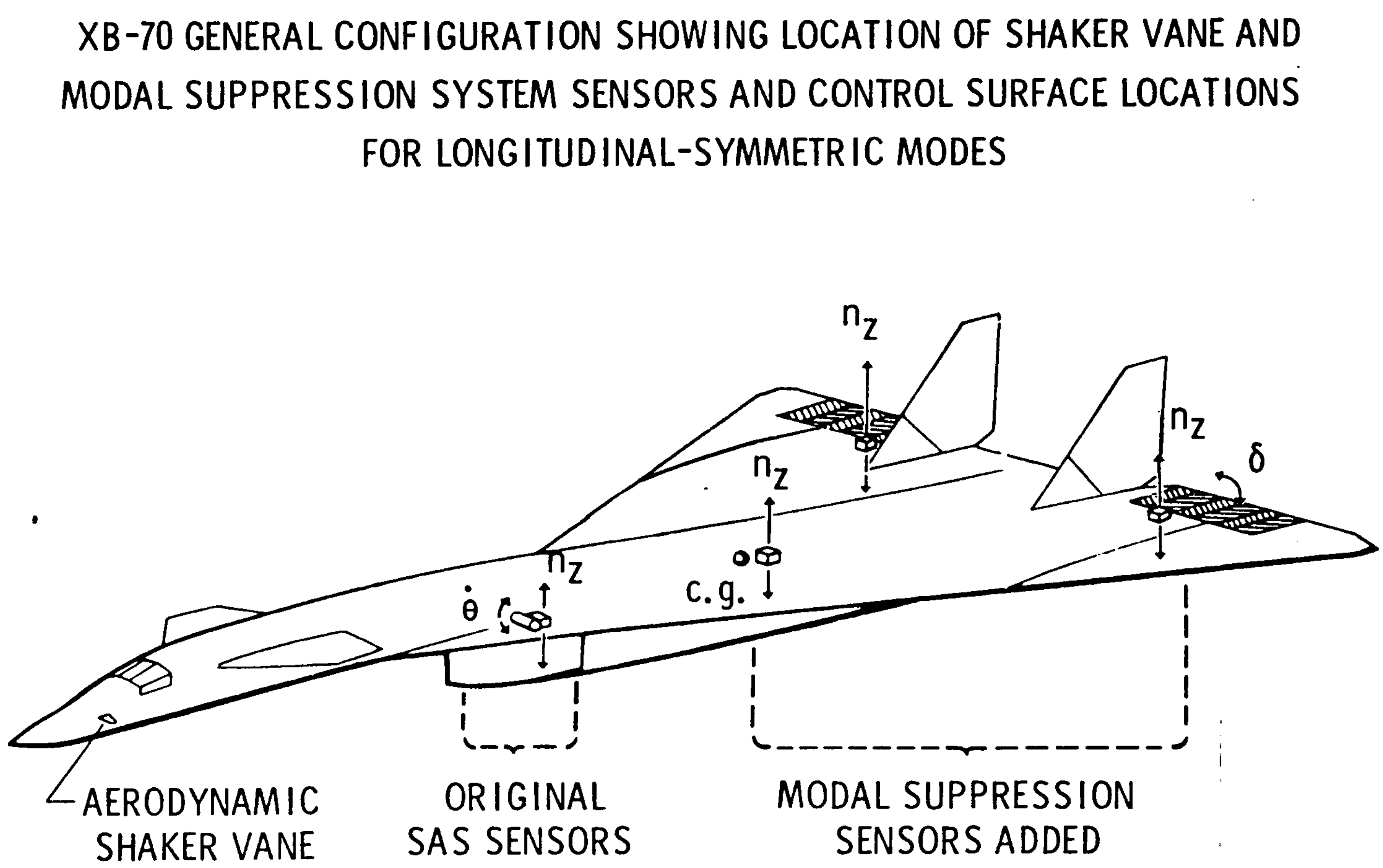


Figure 22.- XB-70 modal suppression system configuration. (Ref. 63)

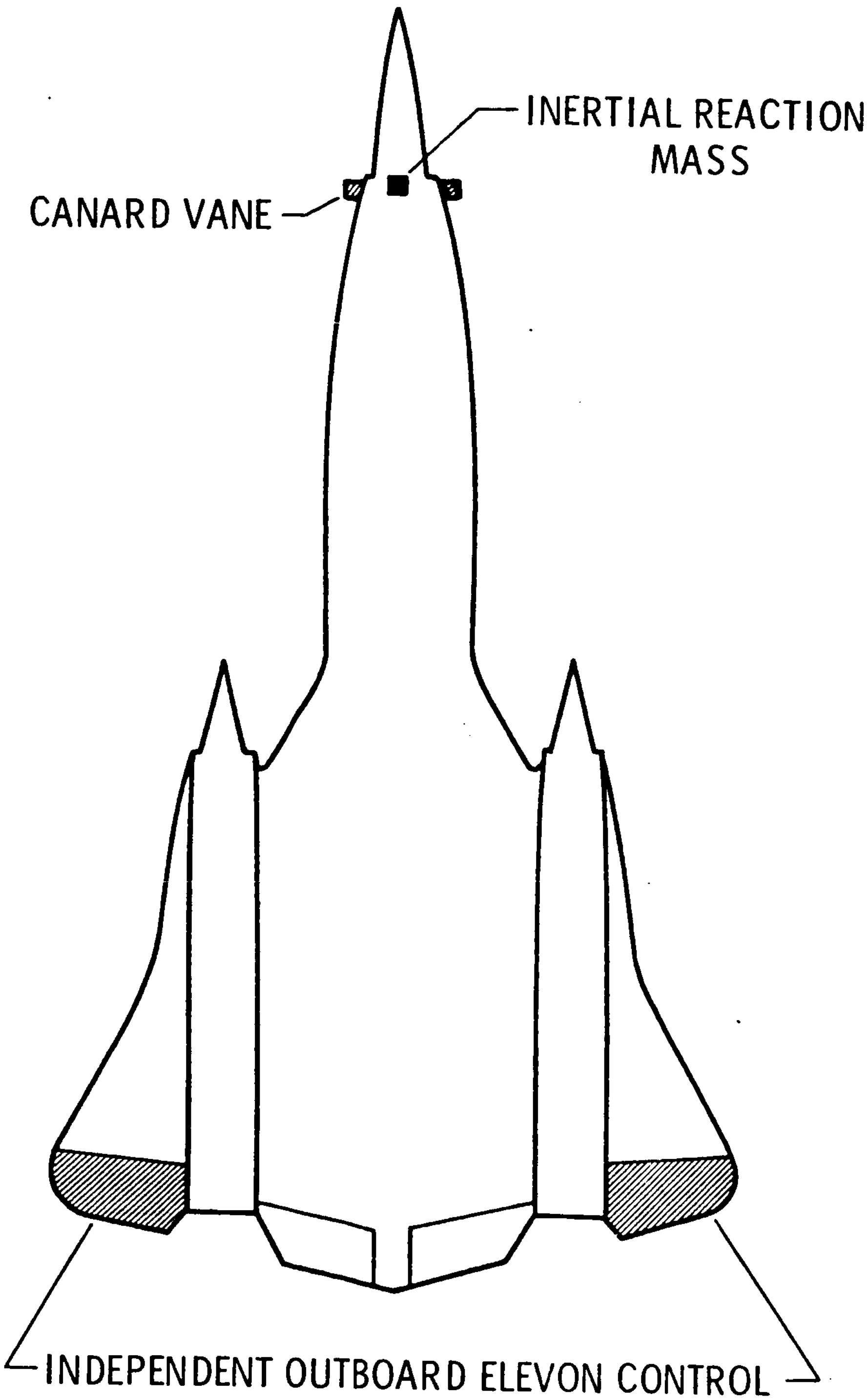


Figure 23.- YF-12A vehicle configuration.

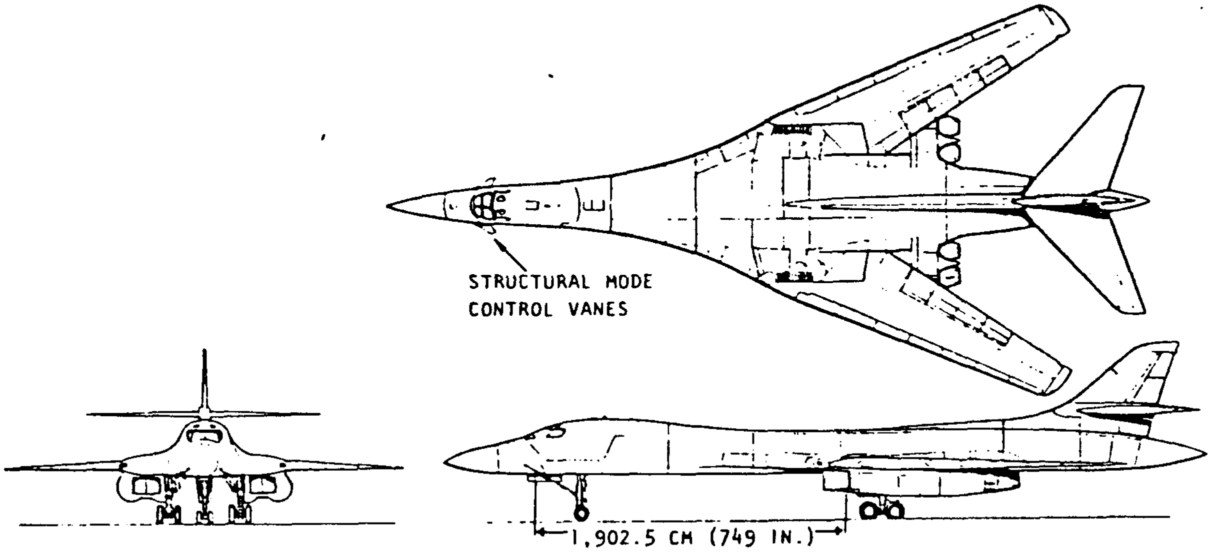


Figure 24.- B-1 aircraft with wings swept aft. (Ref. 65)

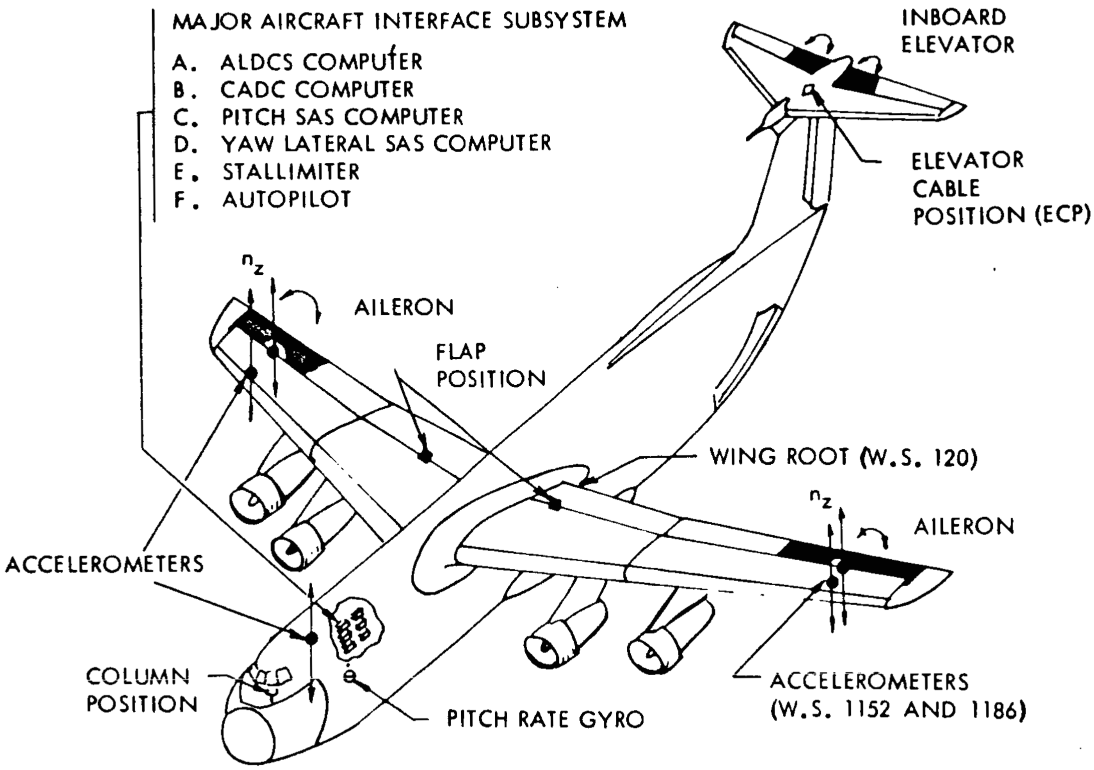


Figure 25.- C-5A ALDCS airplane major components. (Ref. 66)

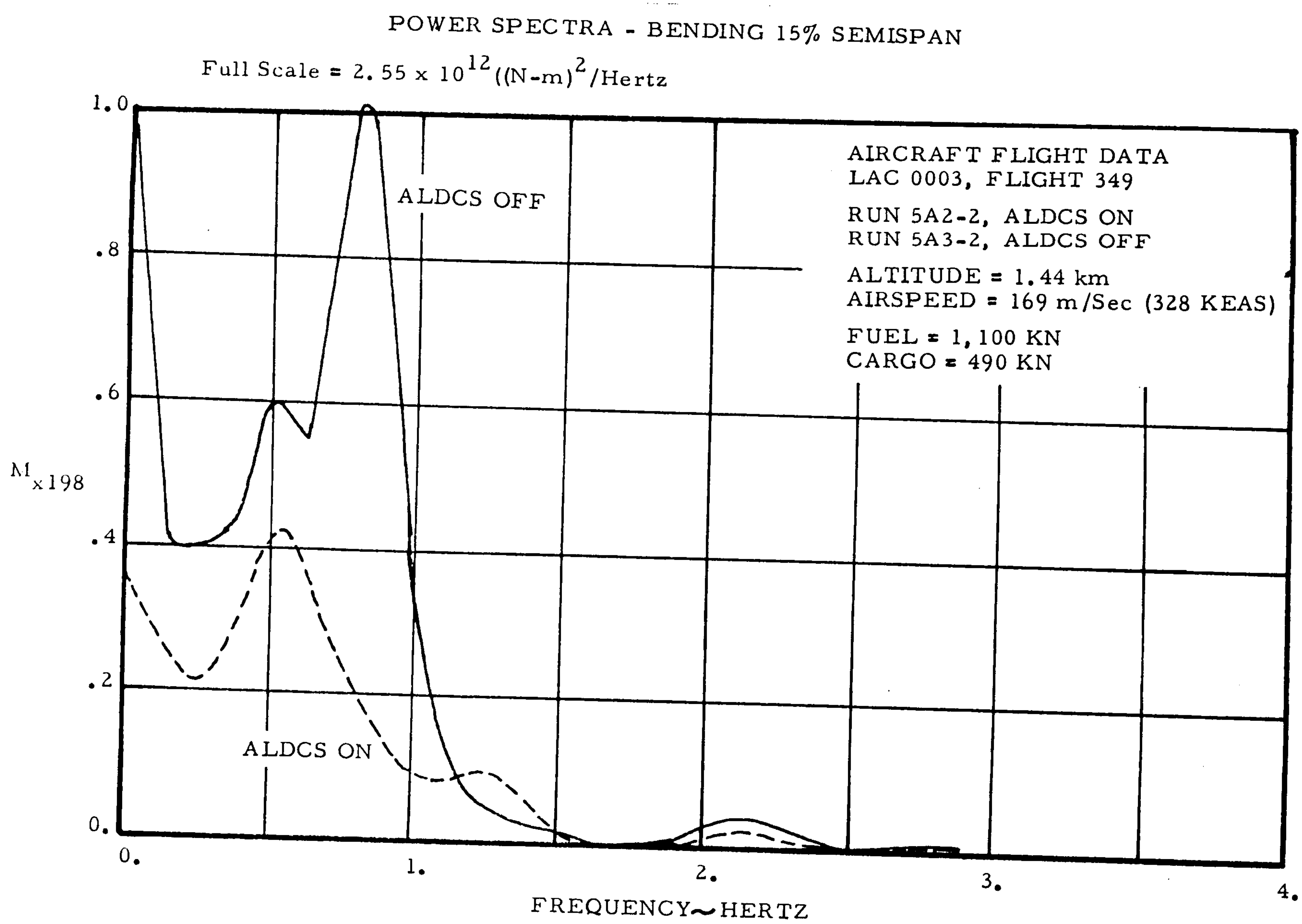


Figure 26.- C-5A response to turbulence. (Ref. 27)

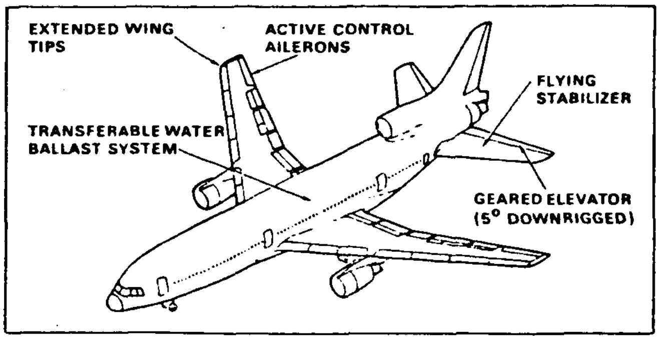


Figure 27.- L-1011 flight test configuration. (Ref. 68)
(copyright American Institute of Aeronautics and Astronautics)

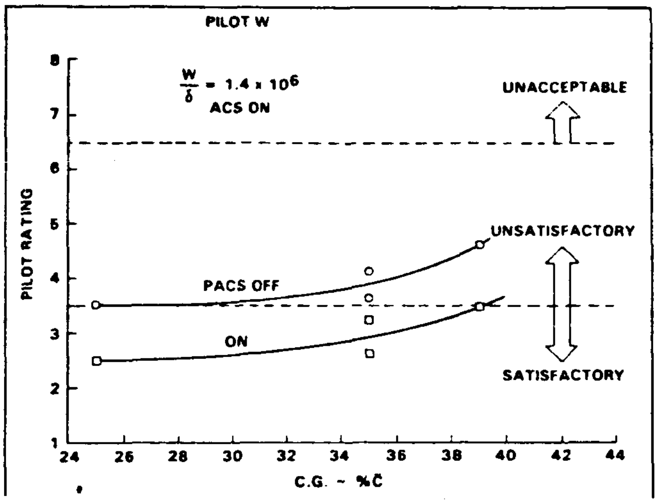


Figure 28. - L-1011 flight test results in cruise. (Ref. 68)
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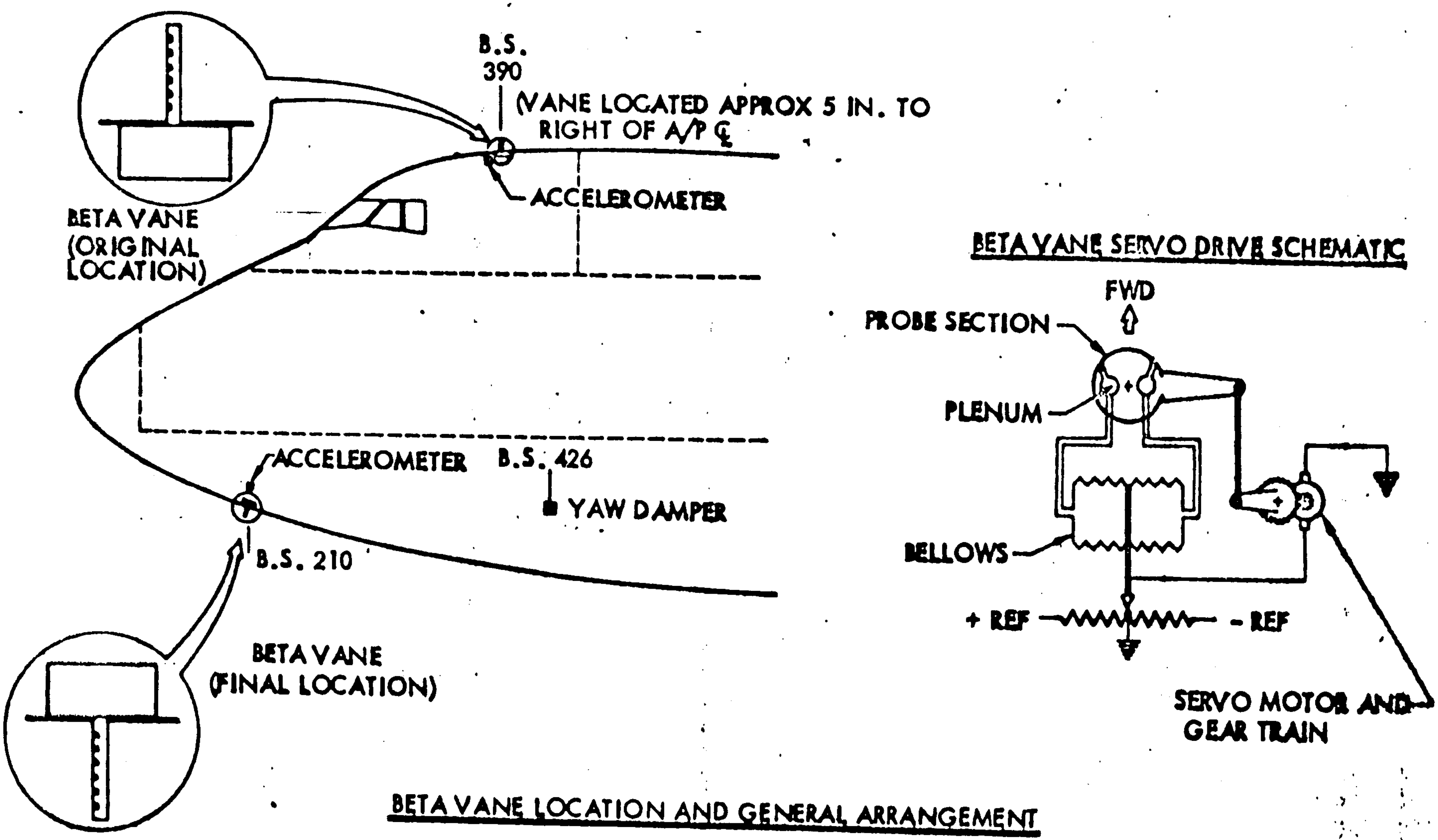


Figure 29. - Lateral gust alleviation system on B-747. (Ref. 70)

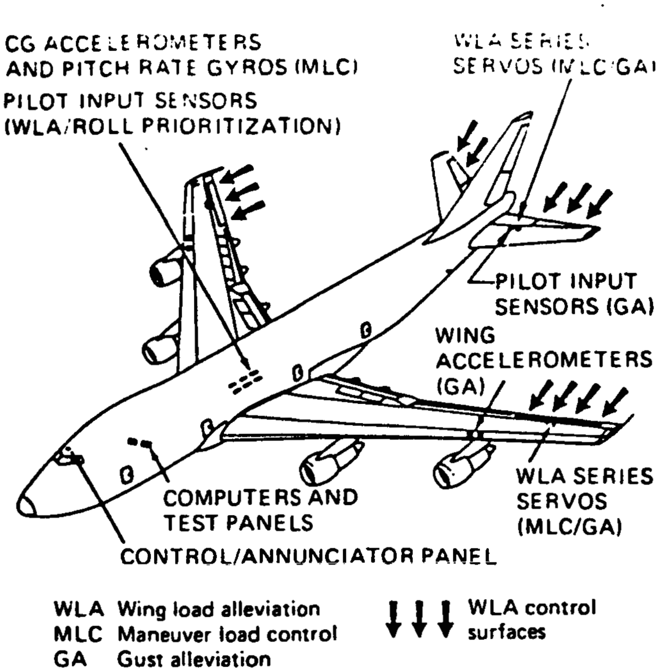
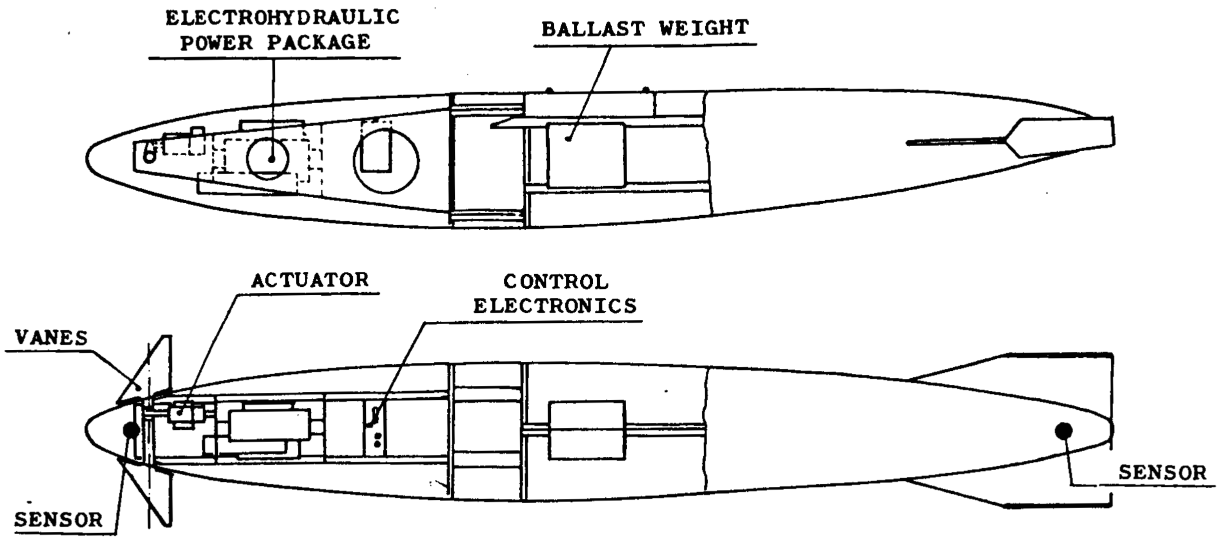
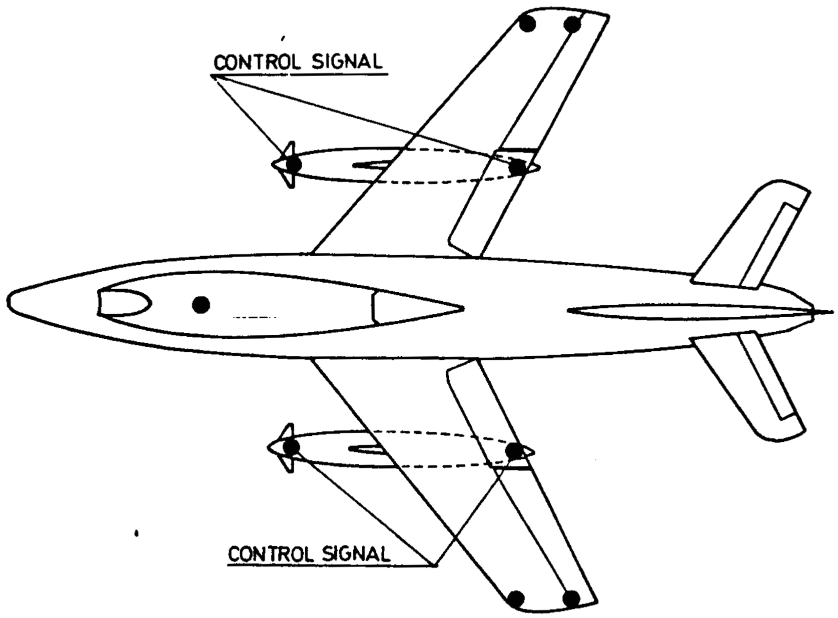


Figure 30. - 747 wing load alleviation components. (Ref. 72)



(a).- External tank with FSS (flutter tank).



(b) Accelerometer locations

Figure 31.- FIAT G91/T3 flutter suppression configuration. (Ref. 76)

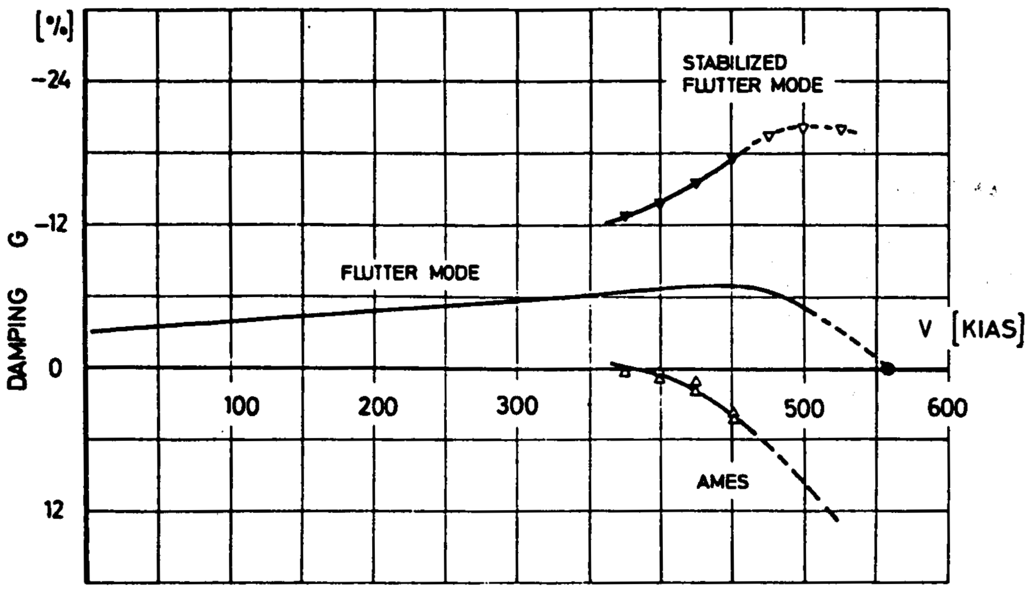


Figure 32.- Example of FIAT G91/T3 flutter suppression flight test results. (Ref. 76)

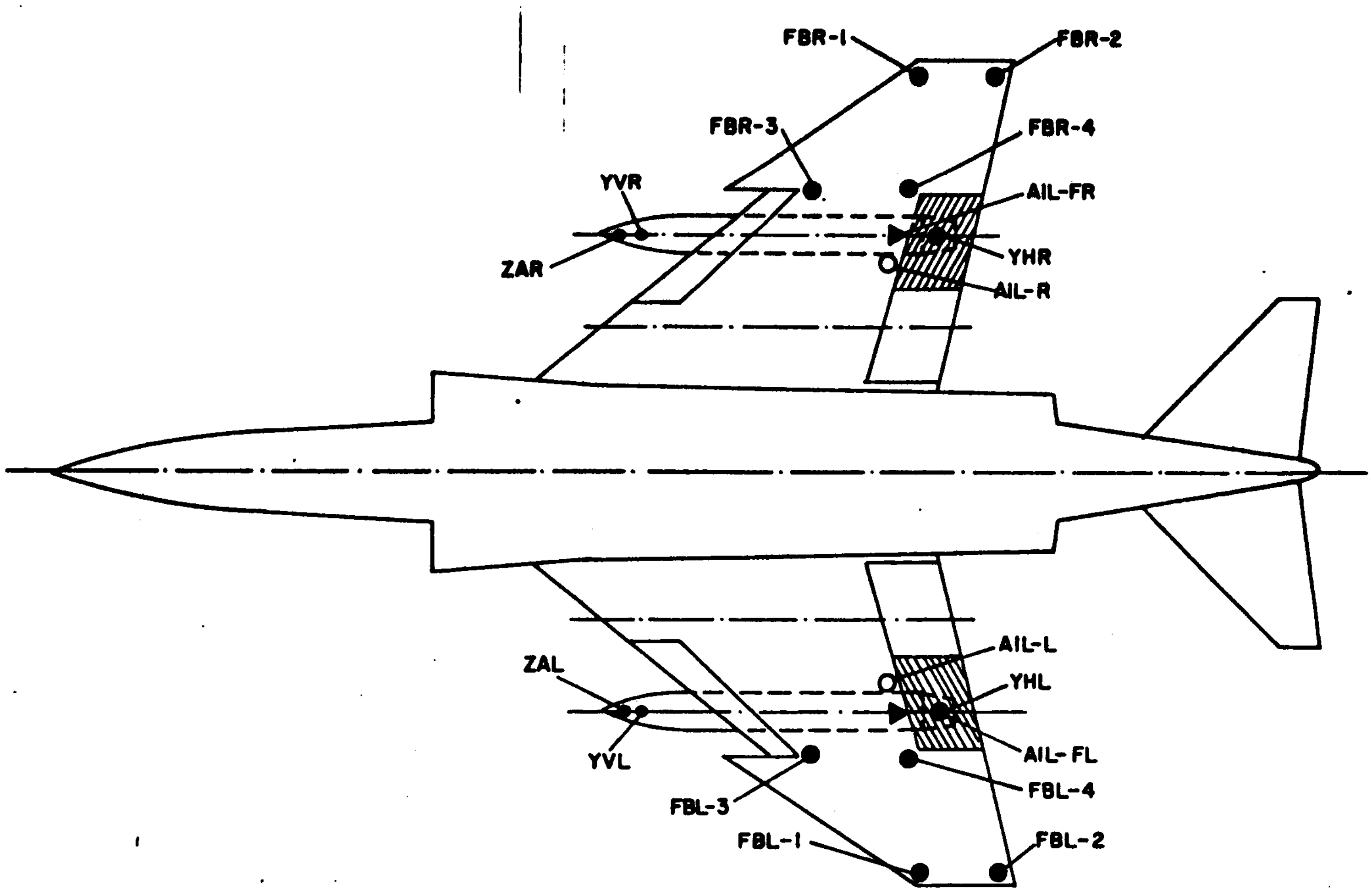


Figure 33.- Locations of sensors and active controls on F-4F flutter suppression test airplane. (Ref. 77)

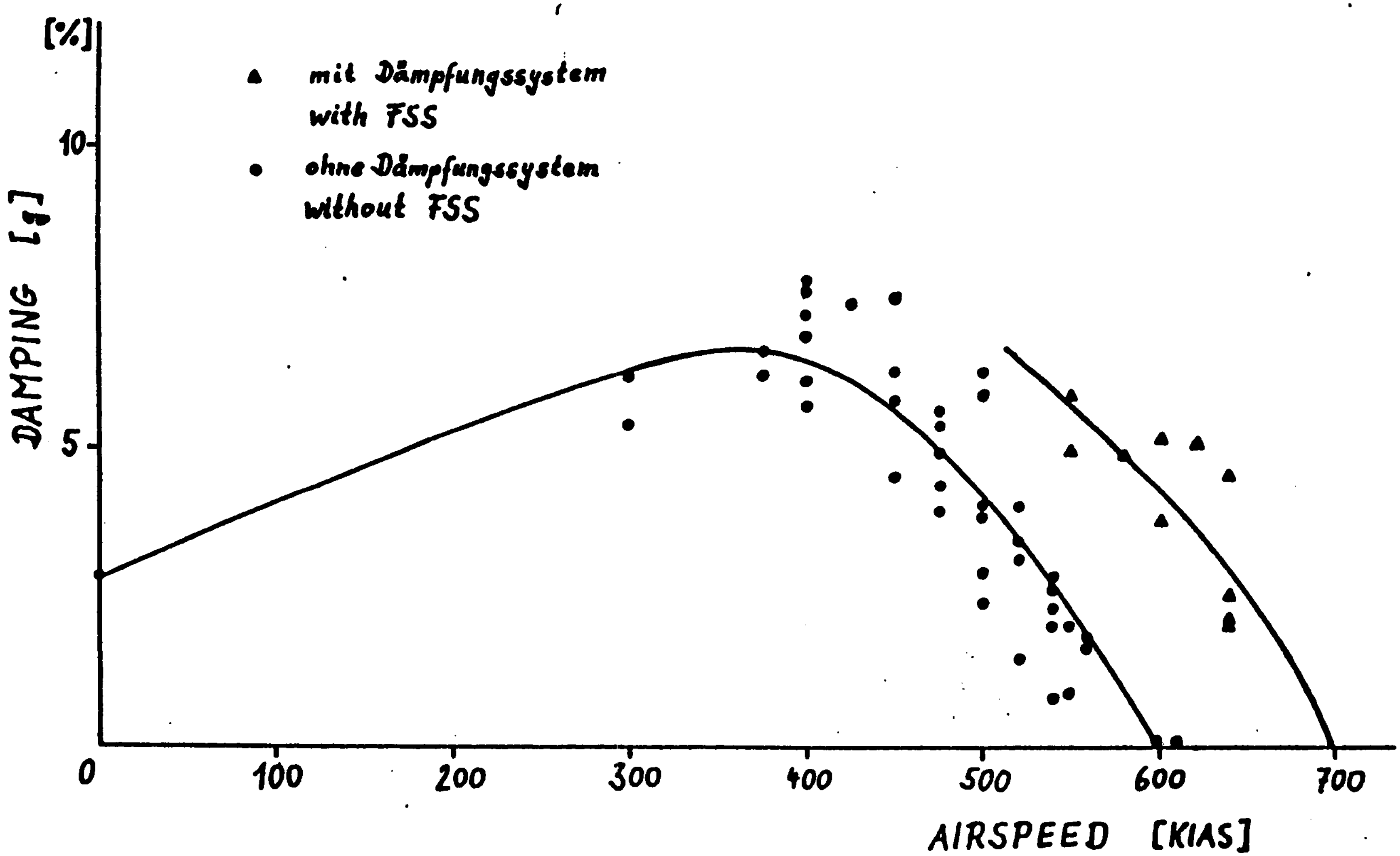


Figure 34.- Possible increase of F-4F flutter speed by the active flutter suppression system. (Ref. 77)

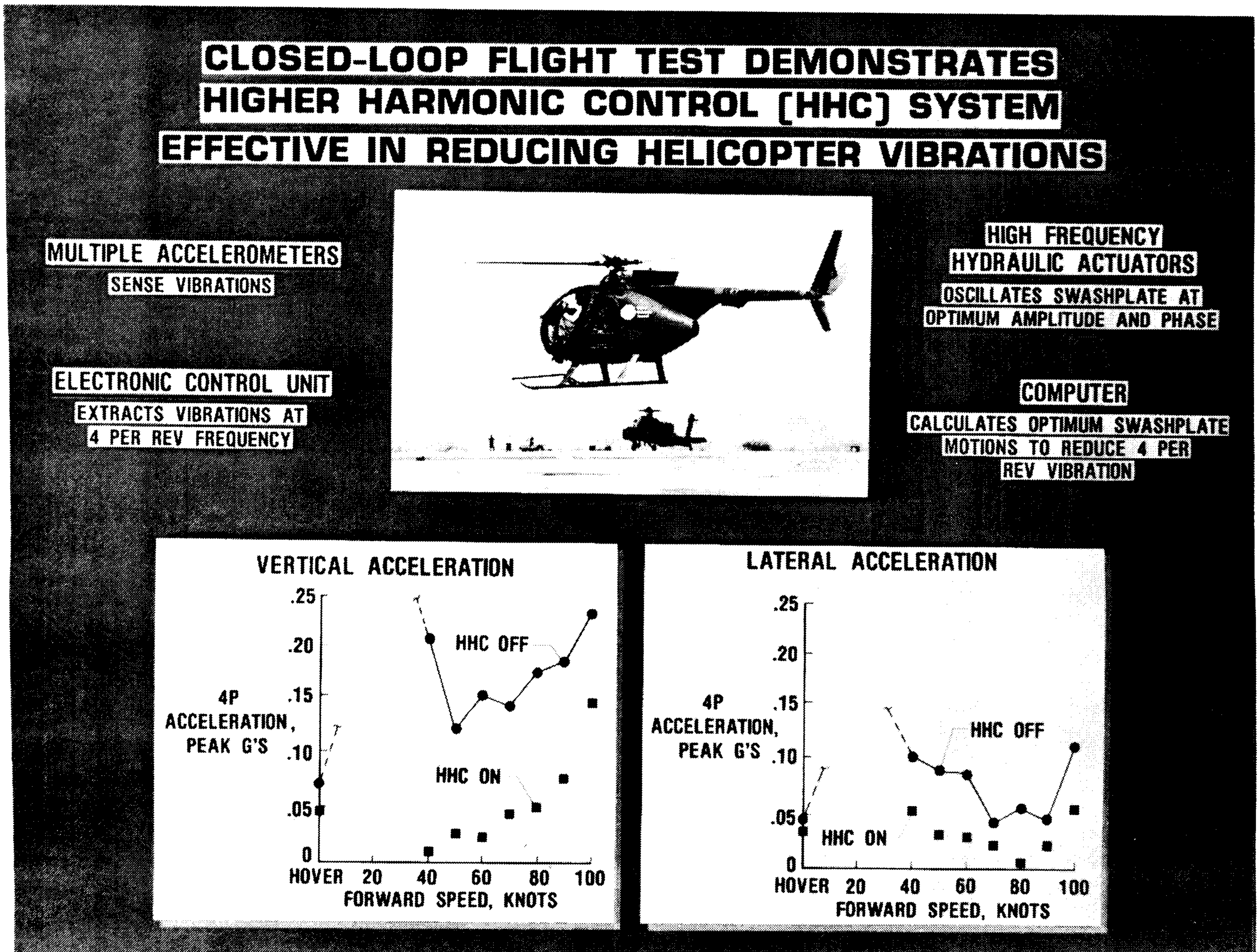


Figure 35.- HHC system components and sample results from initial OH-6A flight tests.

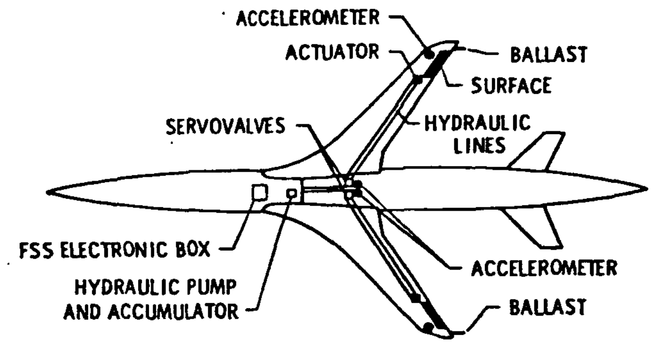


Figure 36.- Planform of the DAST ARW-1 showing the flutter suppression system installation.

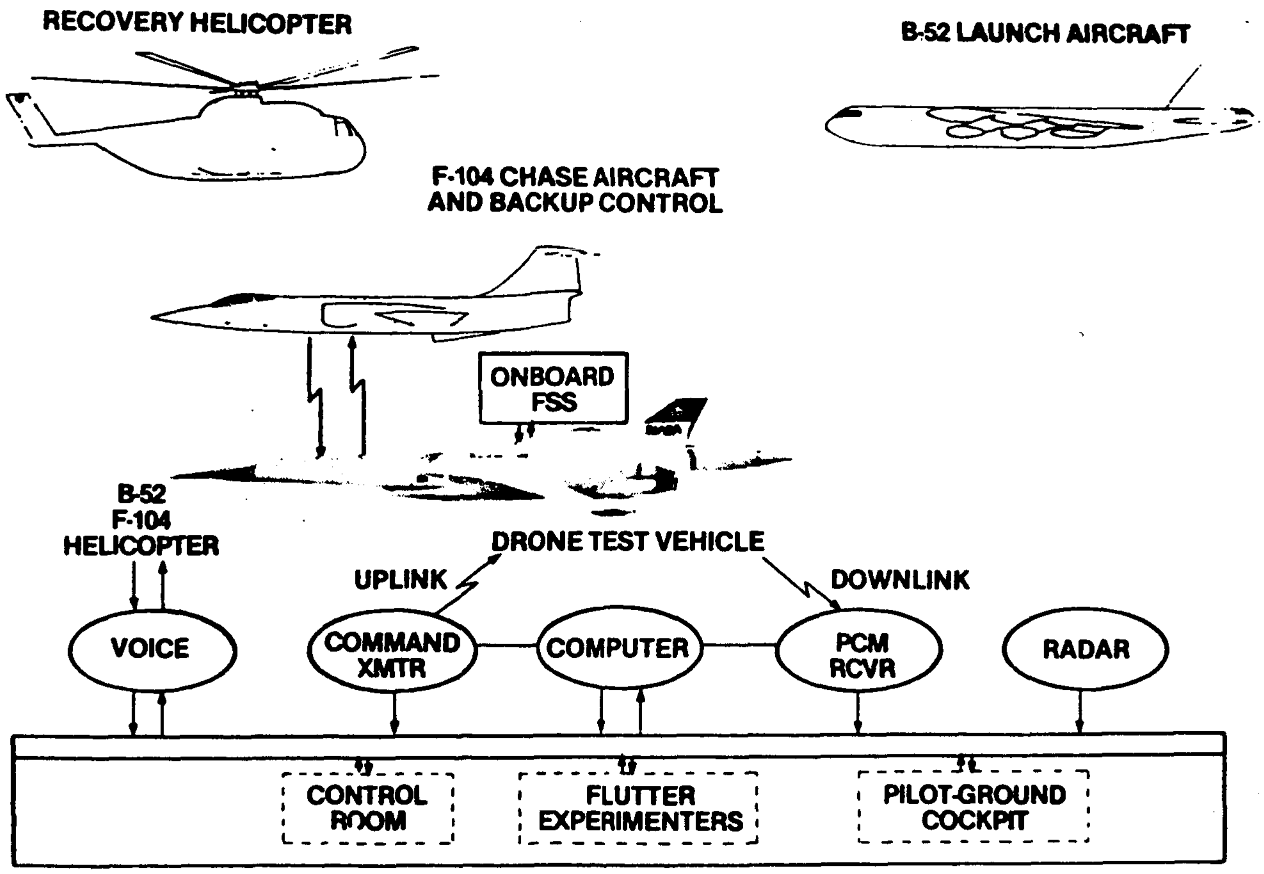


Figure 37.- DAST operational procedure.

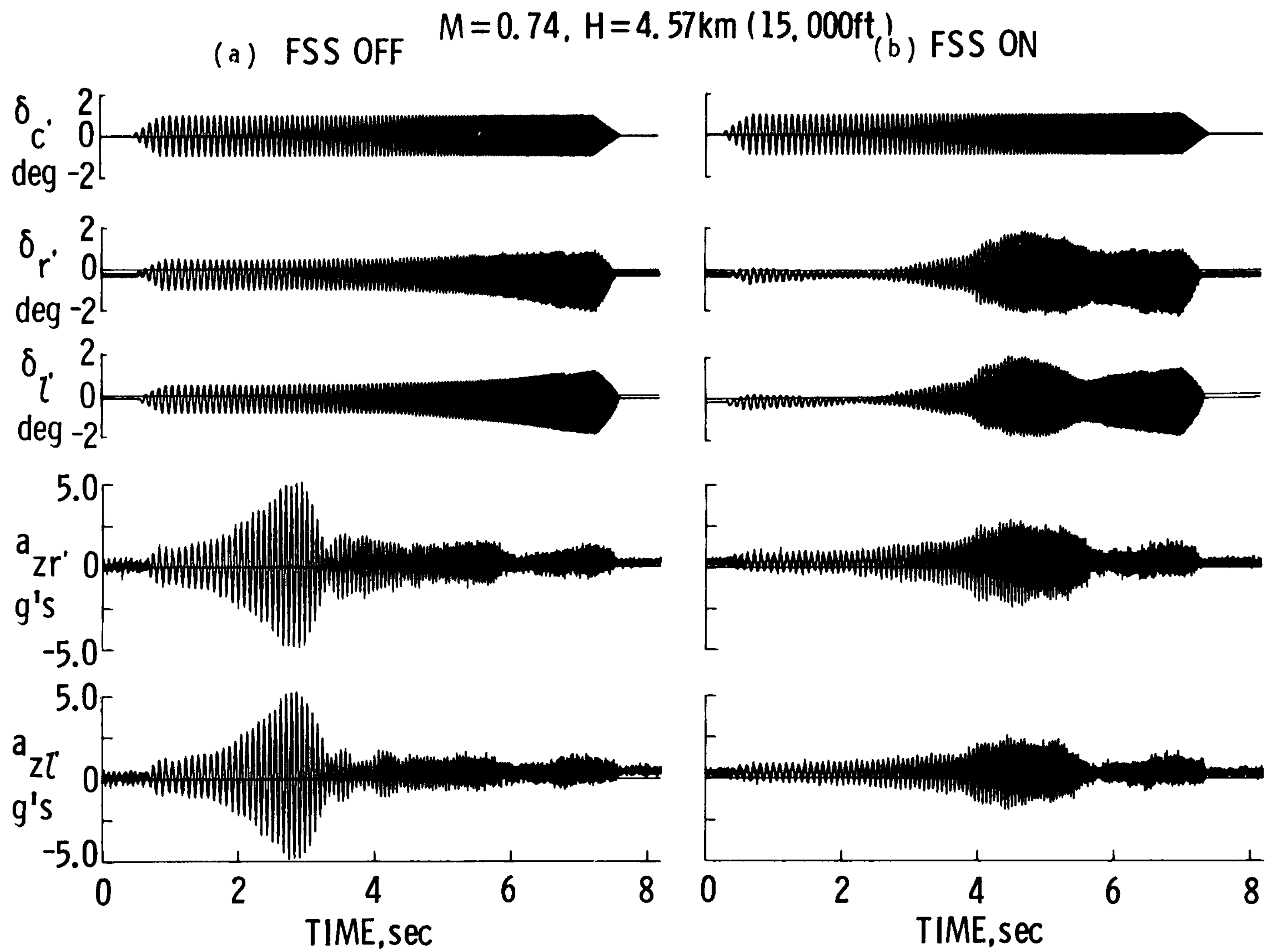
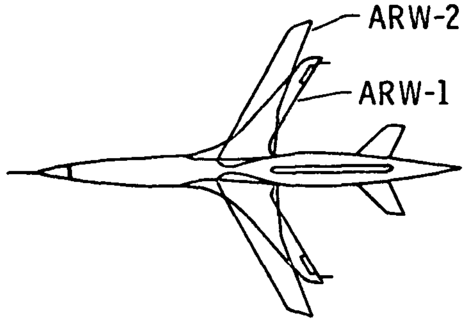


Figure 38. - DAST ARW-1 response to symmetrical frequency sweep excitation.

DAST RESEARCH WINGS



ARW-1

- FLUTTER WITHIN FLIGHT ENVELOPE
- ACTIVE FLUTTER SUPPRESSION SYSTEM
- SUPERCRITICAL AIRFOIL

ARW-2

- FUEL CONSERVATIVE WING DESIGN
    - HIGH ASPECT RATIO (AR = 10.3)
    - LOW SWEEP (= 25°)
    - ADVANCED SUPERCRITICAL AIRFOIL
- MULTIPLE ACTIVE CONTROLS CRITICAL TO FLIGHT OPERATION
    - FSS
    - MLA
    - GLA
    - RSS

Figure 39. - Comparison of DAST ARW-1 and ARW-2 configurations and objectives.

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15. Supplementary Notes

16. Abstract

The paper gives an aeroelastician's perspective of the active controls technology area based on a review of most of the wind-tunnel and flight tests and actual applications of active control concepts since the late sixties. The distinction is made between so-called "rigid-body" active control functions and those that involve significant modification of structural elastic response or stability. Both areas are reviewed in detail although the focus is on the latter area. The basic goals and major results of the various studies or applications are summarized, and the anticipated use of active controls on current and near-future research and demonstration aircraft is discussed. Some of the "holes" remaining in the feasibility/benefits demonstration of active controls technology are discussed.

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